Gerwin Schalk
Jürgen Mellinger

A Practical Guide to Brain-Computer Interfacing with BCI2000

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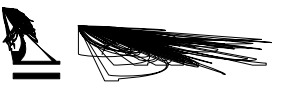

A Practical Guide to Brain–Computer Interfacing with BCI2000

General-Purpose Software for Brain–Computer Interface Research, Data Acquisition, Stimulus Presentation, and Brain Monitoring

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The hope is that, in not too many years, human brains and computing machines will be coupled together very tightly, and that the resulting partnership will think as no human brain has ever thought and process data in a way not approached by the information-handling machines we know today.

J.C.R. Licklider
Man–Computer Symbiosis, March 1960

This book is dedicated to our wives Renate and Ulrike

Preface

What Is BCI2000?

BCI2000 is a general-purpose software platform for brain–computer interface (BCI) research. It can also be used for a wide variety of data acquisition, stimulus presentation, and brain monitoring applications. BCI2000 has been in development since 2000 in a project led by the Brain–Computer Interface R&D Program at the Wadsworth Center of the New York State Department of Health in Albany, New York, USA, with substantial contributions by the Institute of Medical Psychology and Behavioral Neurobiology at the University of Tübingen, Germany. In addition, many laboratories around the world, most notably the BrainLab at Georgia State University in Atlanta, Georgia, and Fondazione Santa Lucia in Rome, Italy, have also played an important role in the project's development.

Mission

The mission of the BCI2000 project is to facilitate research and the development of applications in all areas that depend on real-time acquisition, processing, and feedback of biosignals.

Vision

Our vision is that BCI2000 will become a widely used software tool for diverse areas of research and development.

History

In the late 1990s, Dr. Jonathan Wolpaw, a BCI pioneer at the Wadsworth Center,
recognized the need for a software platform that would facilitate the implementation

of any BCI design. This need was supported by Dr. Niels Birbaumer, another BCI pioneer from the University of Tübingen in Germany. Their joint interest resulted in a meeting that lasted for several days and took place in Tübingen in late 1999. It was attended by Gerwin Schalk and Dennis McFarland from the Wadsworth Center, and Thilo Hinterberger from the University of Tübingen. This meeting resulted in a first set of general system specifications. Because these system specifications were focused on technical flexibility but also practicality, they have not changed since then and there has not been a need to change them.

The next year and a half were characterized by the implementation of the first generation of the BCI2000 system, primarily by Gerwin Schalk and Dennis McFarland at the Wadsworth Center. These efforts culminated in the first successful BCI2000-based experiment in July 2001. The data files generated in that first set of experiments can still be interpreted today with the tools provided by BCI2000. Just like all other BCI2000 data files, these early data sets contained a full record of the parameterization of the experiments, and of the time course of important events such as the timing of stimulus presentation. Thus, it is possible to completely reconstruct all important details of experiments that were conducted many years ago.

During 2002, Jürgen Mellinger at the University of Tübingen joined the BCI2000 project and immediately began to improve the initial system implementation. The project also received initial exposure during the 2nd International BCI Meeting in Rensselaerville, NY, which was organized by the Wadsworth Center. This exposure resulted in the extension of the BCI2000 system to support a P300-based spelling device modeled after the methodology described in [7], and in the first adoption of the BCI2000 system by other research groups (e.g., Dr. Emanuel Donchin, University of South Florida; Dr. Scott Makeig, Swartz Center for Computational Neuroscience, La Jolla; Dr. Melody Moore-Jackson, Georgia State BrainLab). During 2004, Adam Wilson, then a graduate student at the University of Wisconsin at Madison and who has since worked as a postdoctoral associate at the Wadsworth Center, began to use BCI2000 and to contribute to the project.

Since the early years, the design and development of the BCI2000 platform have been subject to two contrasting forces that needed to be appropriately managed. These forces were the desire to develop a robust general-purpose BCI system (i.e., a long-term goal) on the one hand, and the necessity to support many different BCI

experiments in Albany and Tübingen (i.e., short-term goals) on the other hand. In 2005, the continually improving BCI2000 platform and the initial success in the system's dissemination provided the basis for an NIH grant proposal dedicated to the further development and maintenance of the BCI2000 platform. (Initial BCI2000 development had been sponsored by an NIH Bioengineering Research Partnership (BRP) grant to Dr. Jonathan Wolpaw.) In 2006, this grant application was awarded for an initial four-year period by the National Institute of Biomedical Imaging and BioEngineering (NIBIB) of the NIH. This dedicated funding allowed the project team to focus entirely on the needs of the BCI research community rather than simply the needs of individual research projects. The resulting work culminated in the release of BCI2000 V2.0 in early 2008. This version represented the largest single advance since the project's inception. In V2.0, we consolidated and expanded the

existing BCI2000 platform and associated development and maintenance processes to achieve a consistent set of quality core components, comprehensive and up-to-date documentation for users and software engineers, and testing and release management procedures. Since the release of version 2.0, the adoption of the BCI2000 platform has accelerated further. Many scientists and engineers are now requesting BCI2000 for purposes other than BCI research.

As we are writing this book, BCI2000 V3.0 is about to be released. This system increases performance (particularly on machines with multiple processor cores), supports VisualStudio and MinGW in addition to Borland/CodeGear compilers, and further modularizes BCI2000 components.

Impact to Date

BCI2000 has already had a substantial impact on BCI and related research. As of December 2009, BCI2000 has been acquired by nearly 500 laboratories around the world. The original article that described the BCI2000 system [19] has been cited more than 200 times, and was recently awarded a Best Paper Award of 2004 by IEEE Transactions on Biomedical Engineering. Furthermore, a review of the literature revealed that BCI2000 has been used in studies reported in more than 120 peer-reviewed publications. These publications include some of the most impressive BCI demonstrations and applications reported to date. E.g.: the first online brain–computer interfaces using magnetoencephalographic (MEG) signals [15] or electrocorticographic (ECoG) signals [8, 11, 12, 23]; the first multi-dimensional BCI using ECoG signals [22]; the first applications of BCI technology toward restoration of function in patients with chronic stroke [3, 24]; the use of BCI techniques to control assistive technologies [6]; the first real-time BCI use of high-resolution EEG techniques [5]; demonstrations that non-invasive BCI systems can support multi-dimensional cursor movements without [25, 26] and with [14] selection capabilities; control of a humanoid robot by a noninvasive BCI [2]; and the first demonstration that people severely paralyzed by amyotrophic lateral sclerosis (ALS) can operate a sensorimotor rhythm-based BCI [10]. BCI2000 is also supporting the only exist-

ing long-term in-home application of BCI technology for people who are severely disabled. In these ongoing studies by Jonathan Wolpaw and Theresa Vaughan at the Wadsworth Center, BCI2000-based systems are being placed in the homes of severely disabled people. For the past several years, these individuals have been using the BCI for word processing, email, environmental control, and daily communication with family and friends.

Many studies have used BCI2000 in fields related to BCI research. This includes the first large-scale motor mapping studies using ECoG signals [13, 17]; real-time mapping of cortical function using ECoG [16, 21]; the optimization of BCI signal processing routines [4, 18, 27]; evaluation of steady-state visual evoked potentials (SSVEP) for BCI purposes [1]; and the demonstration that two-dimensional hand movements and finger movements can be decoded from ECoG signals ([20] and [9], respectively). Facilitated by the easy exchange of data and experimental

paradigms that BCI2000 enables, a number of these studies were performed as collaborations among several geographically widespread laboratories. To our knowledge, there have been no comparable large-scale collaborative BCI studies that have not used BCI2000.

Furthermore, BCI2000 has also been: used in demonstrations on national television including NBC, CBS, and CNN; referenced several hundred times in journal articles, media articles, and personal blogs; used or cited in dozens of Masters Theses or Doctoral Dissertations; listed as a significant qualification in curricula vitae; and even mentioned as desirable experience in job postings. The widespread and continually growing success of the BCI2000 platform is strong evidence for its utility.

In summary, BCI2000 is promoting and facilitating the evolution of BCI research and development from isolated laboratory demonstrations into clinically relevant BCI systems and applications useful to people with severe disabilities. As indicated by the above descriptions of its utility for many different aspects of BCI research, by its wide dissemination, and by its prominence in the scientific literature, BCI2000 is fast becoming, or perhaps has already become, the standard software platform for BCI research.

Dissemination

The BCI2000 software is available free of charge for research and educational purposes at http://www.bci2000.org. This web site contains comprehensive project-related information including additional documentation on a wiki and a bulletin board. In addition, the BCI2000 project has organized a number of workshops on the theory and application of the platform: Albany, New York, June 2005; Beijing, China, July 2007; Rome, Italy, December 2007; Utrecht, The Netherlands, July 2008; Bolton Landing, New York, October 2009; and Beijing, China, December 2009.

BCI2000 Benefits

Implementation of real-time software that integrates data acquisition, signal process-

ing, and feedback is complex and difficult. BCI2000 is a platform in which the major technical difficulties have been solved. Thus, it allows a scientist or engineer to spend more time on their research and less time on validating and troubleshooting the technology. In addition, BCI2000 offers several other important benefits:

- An Established Solution BCI2000 comes with proven support for different data acquisition hardware, signal processing routines, and experimental paradigms.
- Facilitates Operation of Research Programs Although a number of software platforms, such as Matlab or LabView, can be used to prototype experimental

paradigms, such prototypes do not have the common data format, software interfaces, or documenting protocols, that are important or even critical for success in large research programs. In contrast, BCI2000 has been designed from the start and developed over many years to support large research programs with many diverse research projects.

- Facilitates Deployment in Multiple Sites The BCI2000 platform does not rely on 3rd-party software components for its operation. Even for compilation, it requires only affordable or free C++ compilers. Thus, both development and deployment of BCI2000 on multiple computers in multiple sites is very economical.
- Cross-platform/compiler Compatibility BCI2000 currently requires Microsoft Windows to operate and Borland's C++ Builder for compilation. BCI2000 V3.0 also supports VisualStudio and MinGW.
- Open License BCI2000 is free and without restrictions for academic and research purposes.

Acknowledgments

Core Team

Project Leader	Gerwin Schalk, Ph.D.
Chief Software Engineer	Jürgen Mellinger, M.E.
Quality Control and Testing	Adam Wilson, Ph.D.

Additional Contributors and Acknowledgments

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Acronyms

ALS	Amyotrophic Lateral Sclerosis
AR	Autoregressive
BCI	Brain–Computer Interface
CAR	Common Average Reference
CSP	Common Spatial Patterns
CPU	Central Processing Unit
ECoG	Electrocorticogram
EEG	Electroencephalogram
EMG	Electromyogram
EOG	Electrooculogram
ERP	Evoked Response
FES	Functional electrical stimulation
FFT	Fast Fourier Transform
fMRI	Functional Magnetic Resonance Imaging
fNIR	Functional Near Infrared
ICA	Independent Component Analysis
IIR	Infinite Impulse Response
LDA	Linear Discriminant Analysis
MEG	Magnetoencephalography
MEM	Maximum Entropy Method
PET	Positron Emission Tomography
SCP	Slow Cortical Potentials
SSVEP	Steady-State Visual Evoked Potential
SWLDA	Stepwise Linear Discriminant Analysis
SVM	Support Vector Machine
TMS	Transcranial Magnetic Stimulation

Part I
User Guide

Chapter 1
Brain–Computer Interfaces

1.1 Introduction

Many patients are afflicted with neurological conditions or neurodegenerative diseases that disrupt the normal information flow from the brain to the spinal cord and eventually to the targets of that information, i.e., the muscles that effect the person's intent. Amyotrophic lateral sclerosis (ALS, or also called Lou Gehrig's disease), spinal cord injury, stroke, and many other conditions impair either the neural pathways controlling muscles, or impair the muscles themselves (Fig. 1.1-A). Those individuals that are most affected may lose all abilities to control muscles. Thus, they lose all options to communicate and become completely locked-in to their bodies.

In absence of reversing the effects of the disorders, there are three principal options for restoring function.

The first option is to substitute the damaged neural pathways or muscles with pathways or muscles that are still functional (Fig. 1.1-B). While this substitution is often limited, it can still be useful. For example, patients can use eye movements to communicate [8, 9] or hand movements to produce synthetic speech (e.g., [2, 3, 16, 17]). The second option is to restore function by detecting nerve or muscle activity above the level of the injury (Fig. 1.1-C). For example, the Freehand prosthesis is restoring hand function to patients with spinal cord injuries [6, 11, 13]. The third option for restoring function is to provide the brain with a new and non-muscular output channel, a brain–computer interface (BCI), for conveying the user's intent to

the external world (Fig. 1.1-D).

1.2 Brain–Computer Interfaces (BCIs)

A brain–computer interface (BCI) is a non-muscular communication system that a person can use to directly communicate his/her intent from the brain to the environment [31]. Thus, a BCI system attaches function to brain signals and thereby creates a new communication channel between the brain and a computer. The language of this communication is in part imposed on the brain (by the use of particular

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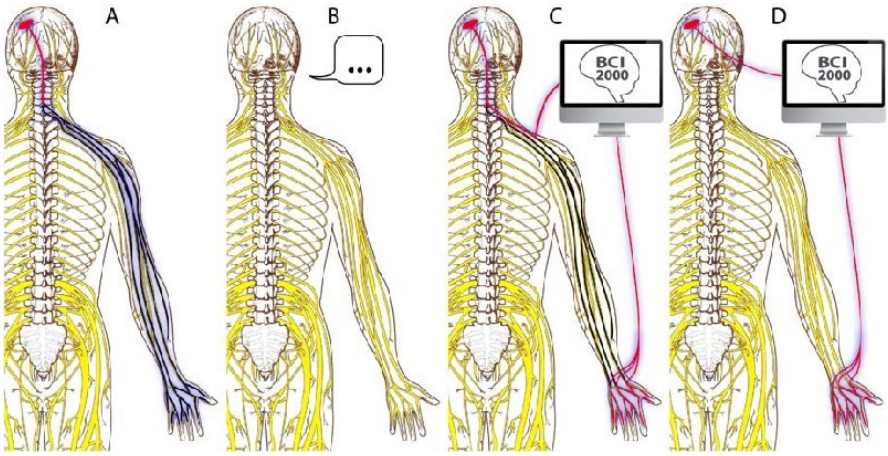

Fig. 1.1 Communication options for the paralyzed. A: Normal output communication channels from the brain to the periphery (e.g., the right hand) are disrupted. B: Option 1: Communication by substitution with other options (such as speech). C: Option 2: Communication by circumventing the impaired pathway. D: Option 3: Adding a new communication channel directly from the brain to an output device or an existing limb – a Brain–Computer Interface (BCI)

brain signal features that the BCI system extracts and uses for device control) and in part negotiated (by the continuous and mutual adaptations of both the user and the system).

Like any communication system, a BCI has an input (i.e., brain signals from the user), an output (i.e., device commands), components that translate the former into the latter, and an operating protocol that determines the onset, offset, and timing of operation. Thus, any BCI system can be described by four components: signal acquisition, which acquires signals from the brain; signal processing, which extracts signal features from brain signals and translates those into device commands; an output device, which acts upon these device commands and thereby effects the user's intent; and an operating protocol that guides operation (see Fig. 1.2). This implies that optimization of the BCI communication process is a complex and multidisciplinary problem that requires the appropriate integration of aspects of neuroscience, electrical engineering, computer science, and human factors.

Using different sensors and brain signals, many studies over the past two decades have evaluated the possibility that BCI systems could provide new augmentative

technology that does not require muscle control (e.g., [1, 4, 5, 10, 12, 14, 15, 18, 20, 21, 23–31]). These brain–computer interface (BCI) systems measure specific features of brain activity and translate them into device control signals. Thus, a BCI system derives and utilizes control signals to effect the user's intent, and it usually does so by allowing the user to make a selection. This selection capacity is often realized using a computer cursor (e.g., [10, 29]), but also in other ways such as controlling an arrow on a dial [20], a moving robot [19], or by controlling other external devices [4, 22]. The key performance characteristics of BCI systems are

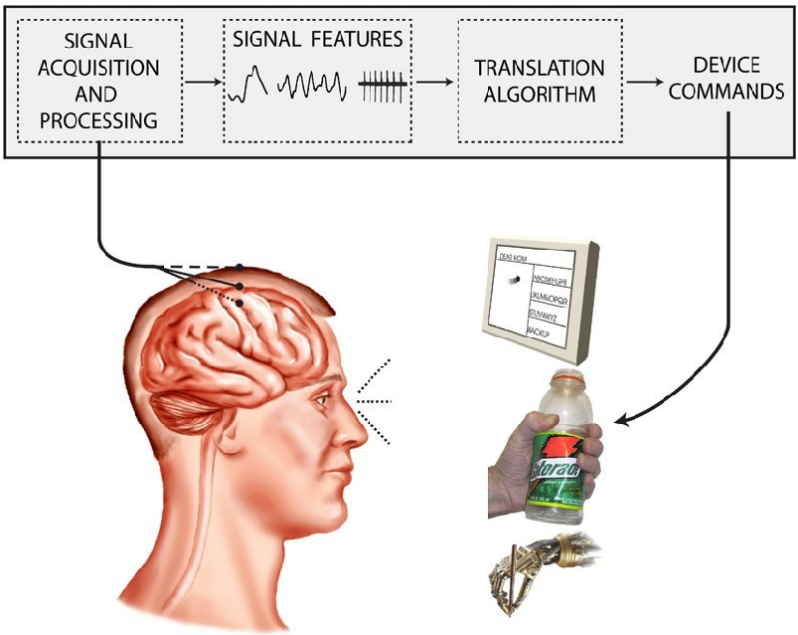

Fig. 1.2 Basic design and operation of any BCI system. Signals from the brain can be acquired by electrodes on the scalp, the cortical surface, or from within the cortex, and processed to extract specific signal features (e.g., time- or frequency-domain measurements) that reflect the user's intent.
These features are translated into commands that operate a device (e.g., a simple word processing
program, a wheelchair, or a neuroprosthesis)

speed (i.e., how long it takes to make a selection) and precision (i.e., the fraction
of executed selections that are consistent with the user's intent). Current systems
allow for one selection within several seconds at a relatively high accuracy (e.g.,
90% accuracy in a binary task). Expressed in bit rate, which combines both speed
and accuracy, the sustained performance of typical BCI systems is still modest. This bit rate typically ranges between 5–25 bits/min [31], although some studies have
reported rates that were higher than that [7].

In consequence, a key problem in the translation of the BCI demonstrations mentioned above into clinically and commercially successful communication systems
for the disabled is to increase the modest performance of current BCI systems. Addressing this problem requires comprehensive evaluations of different BCI methodologies. This process is greatly facilitated by a general-purpose BCI platform that

can readily support any BCI methodology and that facilitates interchange of data
and experimental protocols. This need for a general-purpose BCI platform provided the impetus for the development of the BCI2000 system that is described in this
book.

1.3 Overview

The purpose of this book is to provide an introduction to the BCI2000 system.
Because BCI2000 is a general-purpose system for real-time data acquisition, signal processing, and stimulus presentation, this book is meant for students and researchers who would like to implement real-time systems. Because BCI2000 is not a signal processing toolbox, and not simply a collection of BCI demos, but rather a robust and capable framework for a wide range of experiments, the BCI2000 system generally and this book specifically will be most useful to people who have a serious interest in research in this area.

Because as of yet there are very few comprehensive educational curricula or other general resources on BCI research, we felt that it would be important to include several chapters on basic aspects of BCI systems. This includes a discussion of relevant sensors, relevant brain signals, recording methodologies, and BCI signal processing. This background sets the stage for an introduction to the BCI2000 system, and a tour through its most important features. This is followed by user and programming tutorials, as well as a discussion of advanced concepts and exercises. The book is completed with a comprehensive technical reference.

We use several text conventions in this book when we describe BCI2000 or give step-by-step instructions. These conventions are described briefly here.

- Menu items in BCI2000 or other programs are shown as File.
- Button text in BCI2000 or other programs is also shown as Start.
- Parameter names (e.g., within the BCI2000 configuration window) appear as SubjectName.
- Displayed messages appear on the screen during testing.
- Website URLs, such as www.bci2000.org, are shown underlined.
- File locations appear as `c:/BCI2000/prog/operat.exe`.
- C++ code segments appear as `cout << "Hello World." << endl;`

In several places in the book, the reader is provided with step-by-step instructions to complete a tutorial. These instructions appear in a text box with numbered instructions, such as

Example Instructions

1. Start BCI2000.
2. Press Config.

3. ...

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Chapter 2
Brain Sensors and Signals

2.1 Relevant Sensors

A variety of sensors for monitoring brain activity exist, and could in principle provide the basis for a BCI. These include, besides electroencephalography (EEG) and more invasive electrophysiological methods such as electrocorticography (ECoG) and recordings from individual neurons within the brain, magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and optical imaging (i.e., functional Near InfraRed (fNIR)). However, MEG, PET, fMRI, and fNIR are still technically demanding and expensive, which impedes widespread use. Despite these impediments, several studies have recently explored the value of these modalities for BCI research [10, 11, 42, 60, 82, 97, 98, 108–110, 118]. Furthermore, PET, fMRI, and fNIR, which depend on metabolic processes, have long time constants and thus seem to be less amenable to rapid communication. At present, non-invasive and invasive electrophysiological methods (i.e., EEG, ECoG, and single-neuron recordings, see illustration in Fig. 2.1)are the only methods that use relatively simple and inexpensive equipment and have high temporal resolution. Thus, these three alternatives are at present the only methods that can offer the possibility of a new non-muscular communication and control channel – a practical brain–computer interface.

The first and least invasive alternative uses EEG, which is recorded from the scalp [6, 22, 39, 40, 54, 59, 61, 64, 73, 76, 101, 106, 114, 116, 117]. These BCIs support much higher performance than previously assumed, including two- and three-dimensional cursor movement [59, 66, 114]. However, the acquisition of such high

levels of control typically requires extensive user training. Furthermore, EEG has
low spatial resolution, which will eventually limit the amount of information that
can be extracted, and it is also susceptible to artifacts from other sources.

The second alternative uses ECoG, which is recorded from the cortical surface
[23, 46, 47, 111]. It has higher spatial resolution than EEG (i.e., tenths of millimeters
vs. centimeters [25]), broader bandwidth (i.e., 0–500 Hz [99] vs. 0–50 Hz), higher
characteristic amplitude (i.e., 50–100 µV vs. 10–20 µV), and far less vulnerability
to artifacts such as EMG [3, 25] or ambient noise. While this method is invasive,

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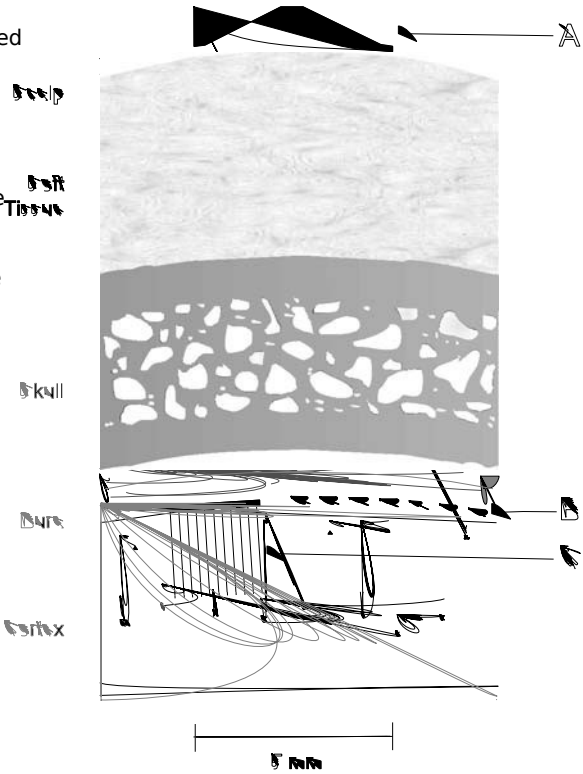

Fig. 2.1 Different types of sensors most commonly used in BCI research. A: Electrodes are placed non-invasively on the scalp (electroencephalography (EEG)). B: Electrodes are placed on the surface of the brain (electrocorticography (ECoG)). C: Electrodes are placed invasively within the brain (single-neuron recordings). (From [112])

the use of these electrodes that do not penetrate the cortex may combine excellent signal fidelity with good long-term stability [7, 49, 52, 119].

The third and most invasive alternative uses microelectrodes to measure local activity (i.e., action or field potentials) from multiple neurons within the brain [21, 32, 45, 67, 84, 92, 95, 103]. Signals recorded within cortex have higher fidelity and might support BCI systems that require less training than EEG-based systems. However, clinical implementations of intracortical BCIs are currently impeded mainly by the difficulties in maintaining stable long-term recordings [20, 93, 100], by the substantial technical requirements of single-neuron recordings, and by the need for continued intensive expert oversight. For these reasons, practically all BCI demonstrations in humans to date have been achieved with, and the examples in this book are using or meant for, EEG or ECoG recordings.

2.2 Brain Signals and Features

2.2.1 Using Brain Signals for Communication

Successful creation of a new communication channel – directly from the brain to an output device – depends on two requirements. The first requirement is the use of an

adequate sensor that can effectively measure the brain signal features that can communicate a user's intent. As described in the previous section, multiple sensors exist that can in principle detect relevant signals. Practicality and speed considerations exclude most of these options, so that almost all BCI systems to date depend on detection of electrophysiological signals using sensors on the scalp, on the surface of the brain, or within the brain. In humans, safety and/or stability issues have confined most studies to electroencephalographic (EEG) recordings from the scalp. The second requirement is the definition and negotiation of a mutual language (i.e., brain signal features such as time-domain or frequency-domain measurements at particular locations), so that, as in any other communication system, the user may use the symbols of this language to communicate intent, and the computer can detect these symbols and effect this intent.

For two reasons, the language of BCI communication cannot be completely arbitrary. First, the brain might simply not be physically able to produce the symbols of this language. For example, one might define the arbitrary language as the amplitude coherence between two different frequency bands at one particular location, and its symbols could be discrete coherence amplitudes, but the brain might simply not be physically able to produce changes in coherence amplitude at the selected frequencies and locations. Second, the brain might be able to produce the symbols of this language, but might not be able to use them to convey intent. For example, one might define the arbitrary language as amplitude modulations at 10 Hz over visual areas of the brain. Many studies have shown that repetitive visual stimuli at particular frequencies (such as 10 Hz) can evoke oscillatory responses in the brain [63], so clearly the brain is physically able to modulate activity at 10 Hz and can thus produce different symbols of that arbitrary language. However, it might not be able to produce these symbols without the visual stimuli, or might not be able to use these symbols to convey intent.

In summary, there is no theoretical basis for selecting the language (i.e., brain signal) that is most useful for BCI communication. Furthermore, any clinically successful BCI will necessarily be under the influence of practical considerations such as risk, benefit, and price. Thus, it is currently unclear which brain signal and which sensor modality (EEG, ECoG, or single neuron recordings) will ultimately be most beneficial given these constraints. At the same time, experimental evidence is able to provide some guidance on which brain signals to utilize for BCI communication. For example, many studies have shown that particular imagined tasks (e.g., hand movements) have detectable effects on particular brain signals. Taking advantage of this phenomenon, people can communicate simple messages using imagery of hand movements. Other studies have shown that the presentation of desired stimuli produces detectable brain signal responses. By presenting multiple stimuli and by detecting the response to the desired stimulus, people can communicate which item they desire. These two possibilities are representative for the phenomena most relevant for BCI communication in humans, and are described in more detail in the following two sections.

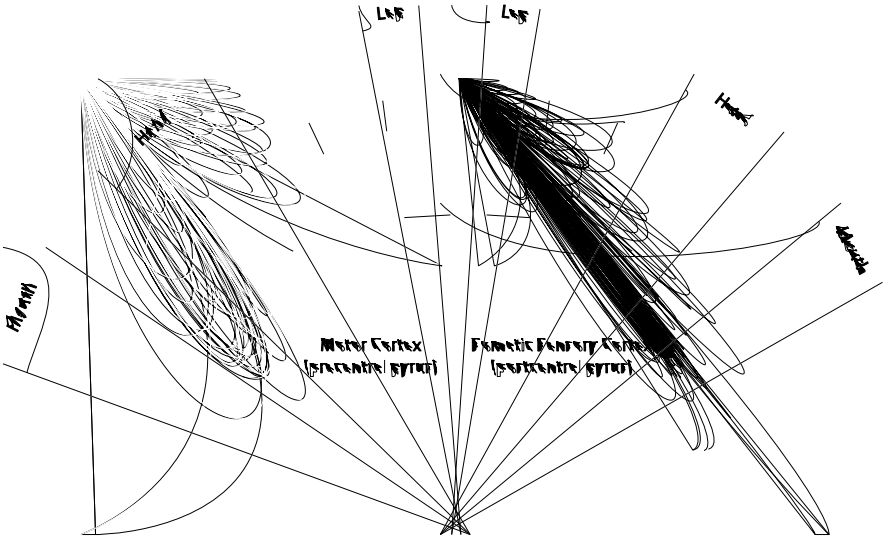

Fig. 2.2 The brain figure on the top shows a vertical cross-section along motor (left) and sensory (right) cortical areas. The motor cortex is displayed in red. Particular areas in the motor cortex are associated with function of particular limbs (i.e., “motor homunculus”). Similarly, sensory cortex is shown in blue. Particular areas in sensory cortex are also associated with sensory function of different limbs (i.e., “sensory homunculus”)

2.2.2 Mu/Beta Oscillations and Gamma Activity

Most people exhibit prominent oscillations in the 8–12 Hz band of the EEG recorded over sensorimotor areas (see Fig. 2.2) when they are not actively engaged in motor action, sensory processing, or in imaginations of such actions or processing [24, 27, 37] (reviewed in [69]). This oscillation is usually called mu rhythm and is thought to be produced by thalamocortical circuits [69]. The lack of modern acquisition and processing methodologies have initially not made it possible to detect the mu rhythm in many people [8], but computer-based analyses have since revealed that the mu rhythm is in fact present in a large majority of people [70, 71]. Such analyses have also demonstrated that the mu rhythm is usually associated with 18–25 Hz beta rhythms. While some of these beta rhythms are harmonics of mu rhythms, some are separable by topography and/or timing from mu rhythms, and thus at least appear to be independent EEG features [57, 70, 71].

Because mu/beta rhythm changes are associated with normal motor/sensory

function, they could be good signal features for BCI-based communication. Movement or preparation for movement, but typically not specific aspects of movements such as its direction [104], are typically accompanied by a decrease in mu and beta activity over sensorimotor cortex, particularly contralateral to the movement. Furthermore, mu/beta rhythm changes also occur with motor imagery (i.e., imagined movement) [57, 72]. Because people can change these rhythms without engaging

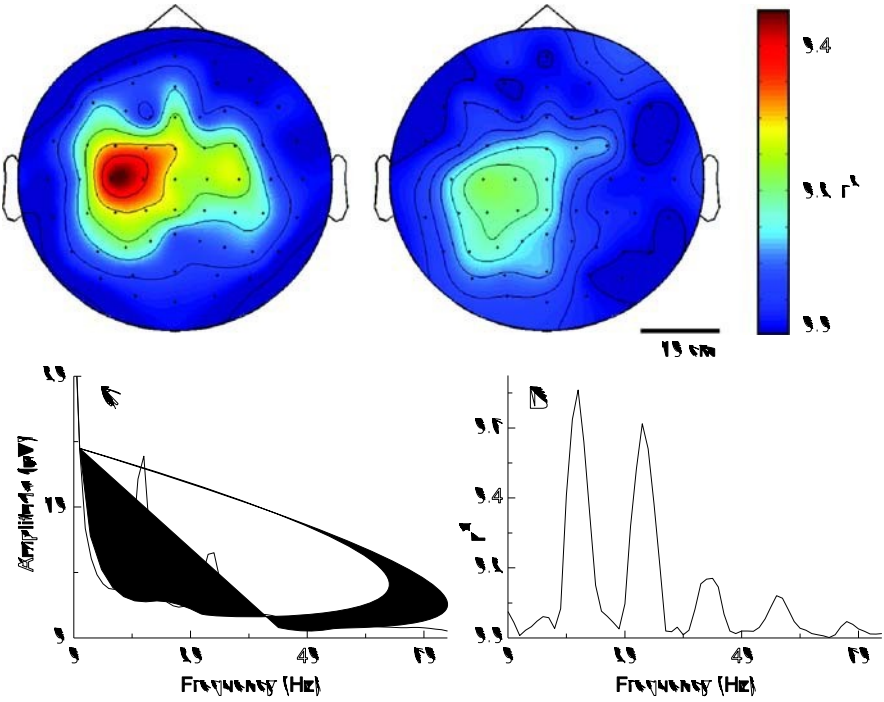

Fig. 2.3 Examples of mu/beta rhythm signals (modified from [85]). A, B: Topographical distribution on the scalp of the difference (measured as r^2 (the proportion of the single-trial variance that is due to the task)), calculated for actual (A) and imagined (B) right-hand movements and rest for a 3-Hz band centered at 12 Hz. C: Example voltage spectra for a different subject and a location over left sensorimotor cortex (i.e., C3 (see [94])) for comparing rest (dashed line) and imagery (solid line). D: Corresponding r^2 spectrum for rest vs. imagery. Signal modulation is focused over sensorimotor cortex and in the mu- and beta-rhythm frequency bands

in actual movements, these rhythms could serve as the basis for a BCI. Figure 2.3 shows the basic phenomenon of mu/beta-rhythm modulations in the EEG.

Similar to EEG, activity in the mu/beta bands recorded using ECoG also decreases with motor tasks [12, 14, 28, 48, 62, 77, 96]. In addition, activity in the gamma range (i.e., >40 Hz) has been found to increase with these tasks [13, 47, 48, 62]. With isolated exceptions (e.g., [74]), task-related changes in these higher frequencies have not been reported in the EEG. There are indications that gamma activity reflects activity of local neuronal groups [41, 62], and thus could be most directly reflective of specific details of movement. Indeed, recent studies have shown

relationships of gamma activity with specific kinematic parameters of hand move-
ments [9, 79, 83, 86].

In summary, many studies have shown using EEG [36, 54, 61, 64, 73, 113–116]
or ECoG [23, 46, 47, 87, 111] that humans can use motor imagery to modulate
activity in the mu, beta, or gamma bands, and to thereby control a BCI system.

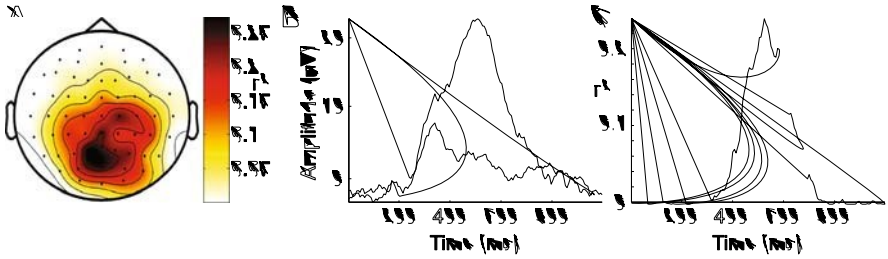

Fig. 2.4 Example characteristics of the P300 response (data courtesy of Dr. Eric Sellers, Wadsworth Center/East Tennessee State University). Left: Topographical distribution of the P300
potential at 500 ms after stimuli, measured as r^2 and calculated between desired and not desired
stimuli. Center: The time courses at electrode location Pz of the voltages for desired (solid line)or not desired (dashed line) stimuli. Right: Corresponding r^2 time course

2.2.3 The P300 Evoked Potential

In addition to brain responses modulated by motor action or motor imagery, evoked
potentials may also be useful for BCI operation. For example, numerous studies over the past four decades have shown that presentation of infrequent stimuli typically
evokes a positive response (called the “P300” or “oddball” potential) in the EEG
over parietal cortex about 300 ms after stimulus presentation (see [17, 102, 107];
[15, 18, 80] for review; Fig. 2.4). The amplitude of the P300 potential is largest at
the parietal electrode sites and is attenuated as the recording sites move to central
and frontal locations [15]. A P300 is usually elicited if four conditions are met. First,
a random sequence of stimulus events must be presented. Second, a classification
rule that separates the series of events into two categories must be applied. Third,
the user’s task must require using [illegible] category of events must be
presented infrequently [16].

Using experimental paradigms [illegible] our conditions, the P300
potential has been used as the bas[illegible]any studies [1, 5, 19, 22,
33, 68, 78, 88–91, 106]. The classic[illegible] Donchin and colleagues
[22] presents the user with a matrix of characters (Fig. 2.5). The rows and columns
in this matrix flash successively and randomly at a rapid rate (e.g., eight flashes
per second). The user selects a character by focusing attention on it and counting

Fig. 2.5 The classical P300-based spelling paradigm developed by Donchin [19, 22]. Rows and columns of the matrix flash in a block-randomized fashion. The row or column that contains the desired character evokes a P300 potential

how many times it flashes. The row or column that contains this character evokes a P300 response, whereas all others do not. After averaging several responses, the computer can determine the desired row and column (i.e., the row/column with the highest P300 amplitude), and thus the desired character.

2.3 Recording EEG

2.3.1 Introduction

After discussing the brain signals most commonly used for BCI operation, this section describes the relevant principles of brain signal recordings and the types of signal artifacts that are typically encountered. These descriptions are mostly focused on EEG. The same general recording principles also apply to ECoG recordings. While most types of artifacts are typically encountered only with EEG, artifacts can also be detected in ECoG [3]. Brain signals are detected using different types of metal electrodes that are placed on the scalp (EEG) or on the surface of the brain (ECoG). These electrodes measure small electrical potentials that reflect the activity of neurons within the brain. To detect the tiny amplitude of these signals, they first have to be amplified. Any biosignal amplifier measures the potential difference (i.e., the voltage) between two electrodes. In most BCI systems, the second of these two electrodes is always the same, i.e., measurements are “unipolar” rather than “bipolar.” In other words, measurements from all electrodes are referred to one common electrode, which consequently is called “reference,” and typically labeled Ref. To improve signal quality, amplifiers require the connection of a “ground” electrode, which is typically labeled Gnd.

EEG electrodes are small metal plates that are attached to the scalp using a conducting electrode gel. They can be made from various materials. Most frequently, tin electrodes are used, but there are gold, platinum, and silver/silver-chloride (Ag/AgCl) electrodes as well. Tin electrodes are relatively inexpensive and work well for the typical BCI-related application. At the same time, tin electrodes introduce low-frequency drifting noise below 1 Hz, which makes them unsuitable for some applications (e.g., Slow Cortical Potential measurements or low-noise evoked

potential recordings).

An important but often neglected detail: mixing electrodes made from different materials in the same recording will result in DC voltage offsets between electrodes. These offsets are due to electrochemical contact potentials and can often be larger in amplitude than what a typical amplifier can tolerate. This will result in a greatly diminished signal-to-noise ratio. Thus, you should always use electrodes made from the same material in a particular recording.

2.3.2 Electrode Naming and Positioning

The standard naming and positioning scheme for EEG applications is called the 10–20 international system [35]. It is based on an iterative subdivision of arcs on

the scalp starting from particular reference points on the skull: Nasion (Ns), Inion (In), and Left and Right Pre-Auricular points (PAL and PAR, respectively). The intersection of the longitudinal (Ns–In) and lateral (PAL–PAR) diagonals is named the Vertex, see Fig. 2.6-A. The 10–20 system originally included only 19 electrodes (Fig. 2.6-B, [35]). This standard was subsequently extended to more than 70 electrodes (Fig. 2.6-C, [94]). This extension also renamed electrodes T3, T5, T4, and T6, into T7, P7, T8, and P8, respectively. Sometimes, one of the electrodes mounted in these positions is used as reference electrode. More often, the ear lobe or mastoid (i.e., bony outgrowth behind the ear) are used. For example, a typical recording may have the ground electrode placed on the mastoid and the reference on the ear lobe on the opposite side.

Acquiring EEG from more than a single location is necessary to be able to determine the optimum location for the BCI purpose. It also greatly facilitates the identification of signal artifacts. Thus, for research purposes we strongly recommend to record from as many locations as possible – at least from 16. For clinical applications, we suggest to initially record from at least 16 locations. Once effective BCI operation has been established and the optimal locations have been determined, the electrode montage can be optimized to record from fewer locations.

2.3.3 Important Brain Areas and Landmarks for BCIs

The brain consists of several distinct areas and landmarks. The approximate location of these areas and landmarks can be determined from the extended 10–20 system shown in Fig. 2.6-C. One of these landmarks is the central sulcus, which is also called Rolandic fissure. The central sulcus runs approximately along the lines between electrodes CPz–C2–C4 and CPz–C1–C3, respectively. On each hemisphere, the central sulcus divides the brain into the frontal lobe (in frontal direction, i.e., toward the nose) and parietal lobe (in posterior direction, i.e., toward the back of the head). The frontal lobe contains, among other areas, the primary motor cortex, i.e., the area of the brain that is most immediately involved in the execution of movements. The parietal lobe contains, among other areas, primary sensory cortex,

i.e., the area of the brain that is a direct neighbor of the primary motor cortex and
that is most directly involved in processing sensory information from different body
parts. Another important landmark is the Sylvian fissure, which is also called lateral
sulcus. It runs along the lines connecting CP6–C6–FT8–FT10 and CP5–C5–FT7–FT9, respectively. It separates the temporal lobe, an area in the brain responsible for auditory processing and memory, from the frontal and parietal lobes.

2.3.4 Placing Electrodes with a Cap

Accurate placement of many electrodes on the scalp is time consuming and requires practice. EEG caps greatly facilitate this process. These caps are made of elastic

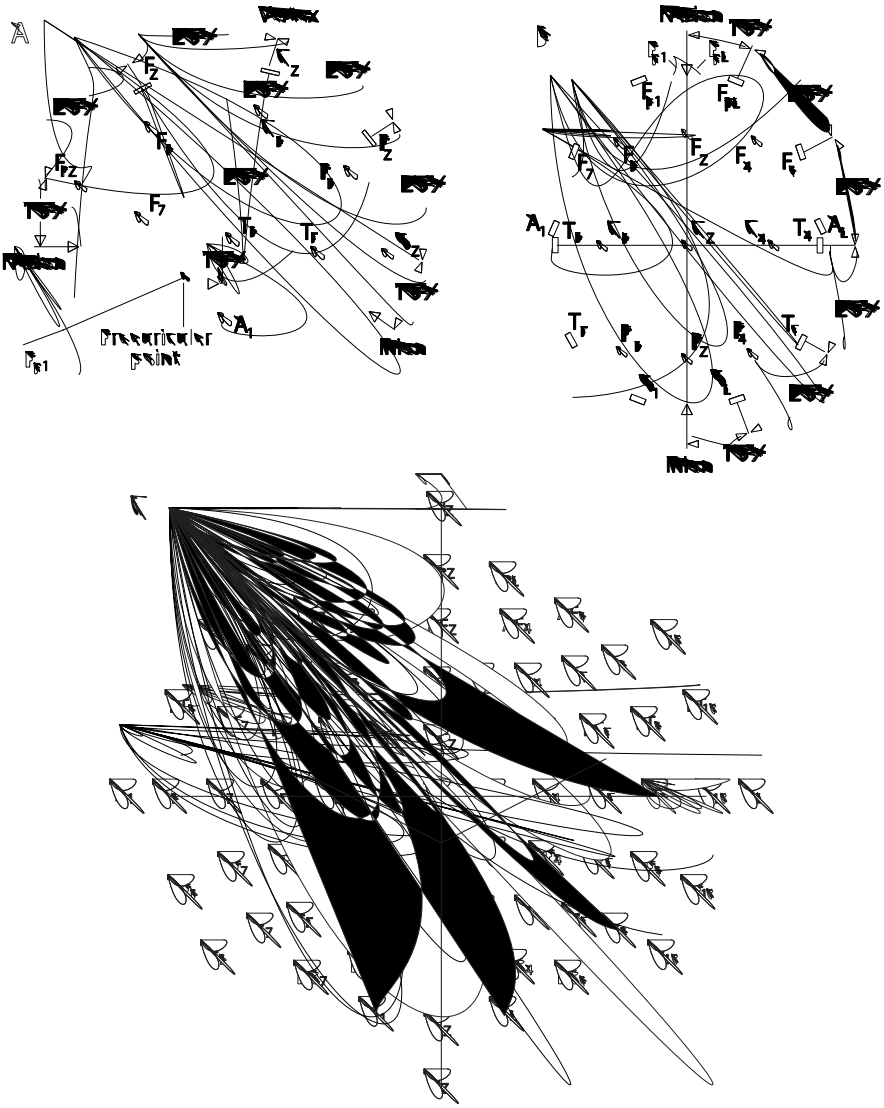

Fig. 2.6 Electrodes on the original 10–20 scheme (figures A and B, re-drawn from [35]). Current
extensions to this scheme define more than 70 locations (figure C, re-drawn from [94])

fabric (often available in different sizes), and electrodes are already fixed in the
proper configuration. One proven technique to place electrodes using such caps is
the following:

- Mark the vertex on the subject's scalp using a felt-tip pen or some other similar
method. Begin by locating the nasion and inion on the subject as indicated in

panel A of Fig. 2.6. Using a tape measure, find the distance between these two

locations. The point half-way between the two points is the vertex. Make a mark at that point for later reference. (Other 10–20 points could be located in a similar manner.)

- Mark scalp positions for Fpz and Oz. The Fpz position is above the nasion 10% of the distance from the nasion to the inion. The Oz position is above the inion the same distance.
- Identify the Cz electrode on the EEG cap and place the cap to position the Cz electrode on the vertex.
- Keeping Cz fixed, slide the cap onto the head.
- While ensuring that Cz does not shift, adjust the cap such that the Fz–Cz–Pz line is on the midline; Fp1–Fp2 line is horizontal, and at the level of the Fpz mark; the O1–O2 line is horizontal, and at the level of the Oz mark.
- You can now fix Ref and Gnd electrodes. These electrodes are attached in one of a few typical configurations. One common configuration is to attach the Ref electrode to one earlobe, and the Gnd electrode to the mastoid on the same side of the head. Another possible configuration is to attach Ref to one mastoid and Gnd to the other mastoid. This choice is influenced by the used cap technology, which may have separate electrodes outside the cap for reference and ground, or may have these electrodes embedded in the cap directly.

2.3.5 Removing Artifacts and Noise Sources

2.3.5.1 Introduction

Electrical power lines use sinusoidal voltages with a frequency of 50 or 60 Hz, depending on your country. Generally, 50 Hz are used in Europe, Asia, Africa, and parts of South America; 60 Hz are used in North America, and parts of South America. Voltages are typically 110 or 230 volts, and thus exceed the EEG's 50 to 100 microvolts by a factor of 2×10^6, or 126 dB. Therefore, mains interference is ubiquitous in EEG recordings, especially if taken outside specially equipped, shielded rooms. Most EEG amplifiers provide a so-called notch filter that suppresses signals in a narrow band around the power line frequency.

Amplifier notch filters are designed to suppress a certain amount of mains in-

terference. When there is mains interference still visible in the signal after activating the amplifier's notch filter, this is often due to high electrode impedance (Fig. 2.7).

2.3.5.2 Artifacts due to Eye Blinks

Eye blink artifacts are generated by fast movements of the eyelid along the cornea, such as during an eye blink. By friction between lid and cornea, this movement results in charge separation, with a dominantly dipolar charge distribution, and the

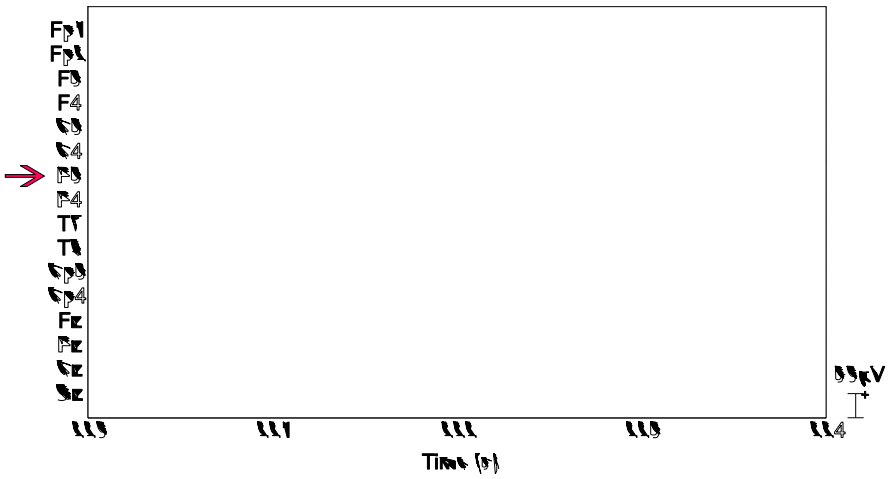

Fig. 2.7 Artifacts due to power line interference. This figure shows an example for one signal
channel (marked by the arrow) that is contaminated by regular high frequency (i.e., 60 Hz) noise

dipole moment pointing in up-down-direction. In the EEG, this effect is recorded
as a positive peak that lasts a few tenths of a second, is most prominent in the
frontopolar region, but propagates to all the electrodes of the montage, attenuating
with distance from the front (Fig. 2.8).

The frequency content of eye blink artifacts is negligible in the alpha band
(around 10 Hz), so they have no strong effect on the use of sensorimotor rhythms.
At the same time, their time-domain amplitude is quite large so that analyses in the

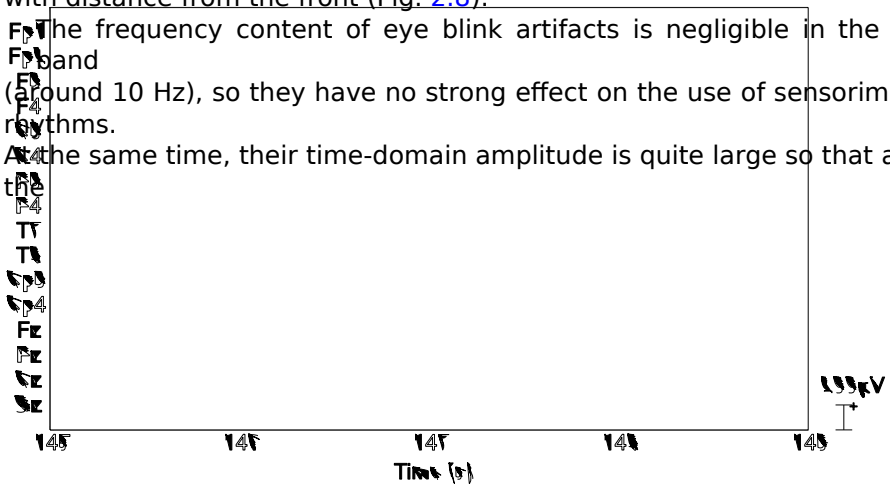

Fig. 2.8 Eye blink artifacts. This figure shows examples for signal contamination by eye blink artifacts. These artifacts are most prominent in frontal channels (channels Fp1 and Fp2), but have
effects on all channels

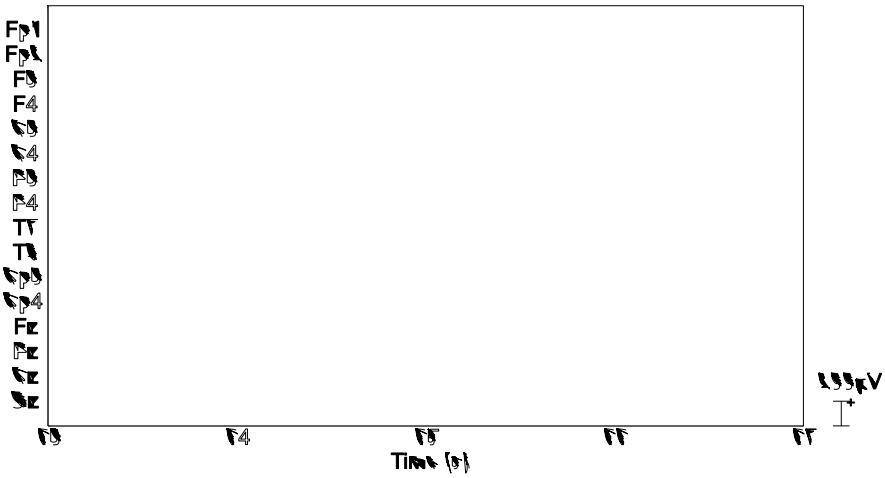

Fig. 2.9 Eye movement artifacts. Eye movements have a prominent effect on many channels. See the positive or negative deflections during early, middle and late parts of this recording

time domain (such as averaged P300 wave forms) can be strongly influenced by
their presence.

2.3.5.3 Artifacts due to Eye Movements

Ocular artifacts (electrooculographic (EOG) signals) are produced by eye move-
ments, and generated by a frictive mechanism that is similar to the one described
above for eye blinks, except that it involves the retina and cornea rather than cornea
alone. The effect on frontopolar and frontotemporal electrodes can be symmetric
or asymmetric, depending whether the movement is vertical or horizontal, respec-
tively. The effect of eye movement artifacts on frequency- or time-domain analysis
is quite similar to that of blink artifacts, except that their frequency content is even
lower, and amplitudes tend to be larger (Fig. 2.9).

2.3.5.4 Artifacts due to Muscle Movements

Muscular artifacts (electromyographic (EMG) signals, Fig. 2.10) must be carefully
checked at the beginning of each recording, and verified throughout the recording.

This is because the frequency distribution of EMG signals is very broad, so that
they have a profound effect on amplitudes in typical mu/beta frequency ranges. The
most common sources of EMG are the muscles that lift the eye brows, and those
that close the jaw. Both groups of muscles can be inadvertently contracted during
an experimental session. Keeping the mouth slightly open (or the tip of the tongue
between the foreteeth) is a good strategy to avoid jaw-generated EMG.

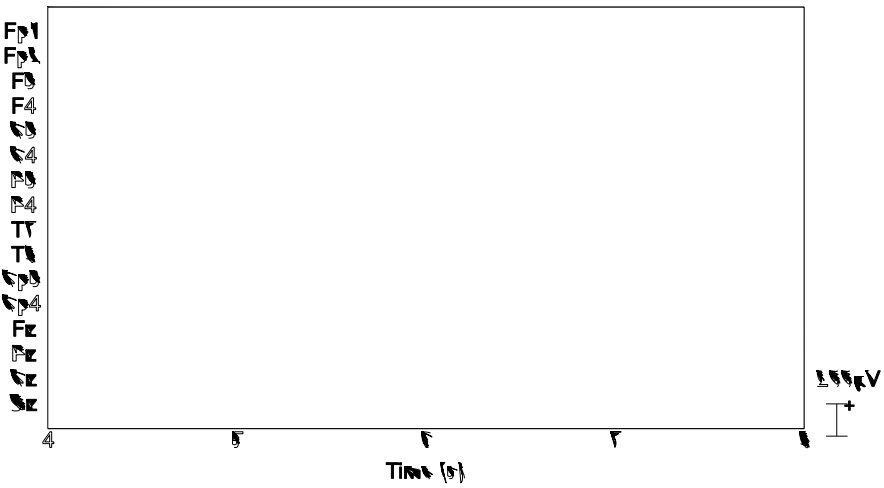

Fig. 2.10 Muscle movement artifacts. Many channels exhibit high frequency noise; in contrast to
the power line interference, this noise is highly variable over time

2.4 BCI Signal Processing

The previous section described the two frequency- and time-domain phenomena
most relevant to human BCI research, i.e., mu/beta rhythms and gamma activity,
and the P300 evoked potential, respectively. Many studies have shown how these
phenomena can be extracted and translated into device commands using differ-
ent methods. All currently used procedures are listed in recent review articles on
BCI feature extraction and translation methods [4, 50, 58]. The following sec-
tions describe an analysis approach that can realize many of these techniques.
This approach is implemented in the example configurations of the BCI2000 soft-
ware.

2.4.1 Introduction

BCI signal processing is a difficult problem. In addition to typical problems faced by any communication system (e.g., signals are contaminated with noise during trans-
mission), it is initially and even during subsequent operation not clear which brain
signals actually carry the message the user wants to communicate. In other words,

it is the task of BCI signal processing to decode a message in a language we do not know much about. Fortunately, experimental evidence can provide some basic guidance. This guidance comes from observations that particular tasks (such as imagined hand movements) have particular effects on specific brain signals (such as the mu rhythm measured at a particular location). Even with this information, the choice of signals and tasks is still difficult, because it is likely that it is suboptimal (so that a completely different signal and task might provide improved performance) and

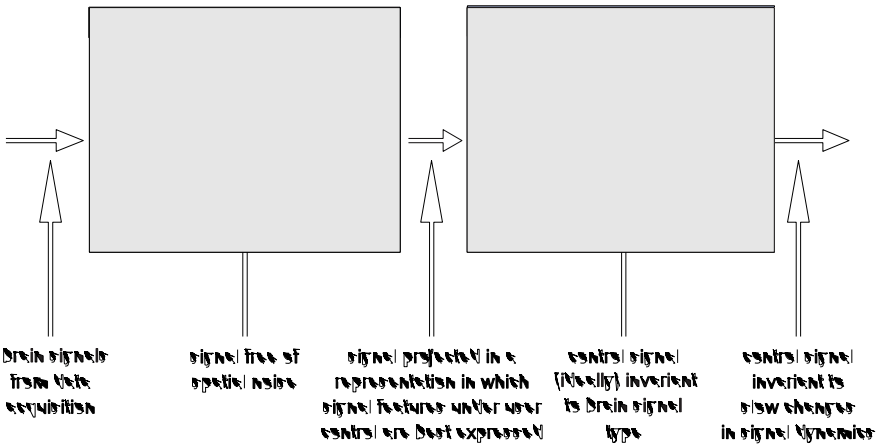
Brain signals from data acquisition
signal free of spatial noise
signal projected in a representation in which signal features under user control are best expressed
control signal (ideally) invariant to brain signal type
control signal invariant to slow changes in signal dynamics

Fig. 2.11 Signal processing model utilized in BCI2000. This model consists of feature extraction and translation and can describe all common BCI methods

because it has to be optimized for each individual. In other words, even when only
considering one possible physiological signal (such as the mu rhythm), the imagery task, best frequencies, and best locations have to be selected for each individual.
The difficulty of choosing signals and tasks could be regarded as the signal iden-
tification problem of BCI communication. Assuming that a good candidate signal
(e.g., the signal amplitude at a particular frequency or location) has been identified,
traditional BCI signal processing usually employs two components to translate these signals into device commands: feature extraction and the translation algorithm.[1]

Feature extraction consists of two procedures: spatial filtering and temporal fil-
tering (Fig. 2.11). Each of these procedures may have different realizations. The
following paragraphs describe those realizations that are relevant to sensorimotor
rhythm and P300 processing.

2.4.2 Spatial Filtering

The initial step in feature extraction is the application of a spatial filter that may
have many possible realizations. The purpose of the spatial filter is to reduce the ef-
fect of spatial blurring. Spatial blurring occurs as an effect of the distance between
the sensor and the signal sources in the brain, and because of the inhomogeneities

of the tissues in between. Different approaches to spatial filtering have attempted

[1]We use the term translation algorithm instead of classification throughout this book, because the typically continuous nature of the device control signals produced by BCI signal processing is better expressed by the term translation algorithm rather than the discrete output that is typically implied by the term classification.

to reduce this blurring, and thus to increase signal fidelity. The most sophisticated approaches attempt to deblur signals using a realistic biophysical head model that is optimized for each user and whose parameters are derived from various sources such as magnetic resonance imaging (MRI) (e.g., [44]). While these approaches do increase signal quality in carefully controlled experiments, they are currently impractical for most experiments and for clinical applications. Other approaches do not require external parameterization of a complex model, but rather are simply driven by the signals that are submitted to it. For example, Independent Component Analysis (ICA) has been used to decompose brain signals into statistically independent components [51], which can be used to get a more effective signal representation. (This approach is called blind deconvolution in microscopy applications (e.g., [105]).) Even though these approaches have less demanding requirements than the more comprehensive modeling approaches, they require non-trivial calibration using sufficient amounts of data, and they produce output signals that will not necessarily correspond to actual physiological sources in the brain. Furthermore, while ICA optimizes statistical independence of brain signals, and can thus lead to more compact signal representations, it does not guarantee to optimize the discriminability of different brain signals in different tasks. Consequently, these complex model-based and data-driven approaches may not be amenable or desirable for typical BCI experimentation. A more appropriate technique is Common Spatial Patterns (CSP) [29, 81]. This technique creates a spatial filter (i.e., weights for the signals acquired at different locations) that correspond to their importance in discriminating between different signal classes. Finally, even simpler deblurring filters have been shown to be effective and yet practical [56]. These filters are essentially spatial high-pass filters with fixed filtering characteristics. Typical realizations include Laplacian spatial filters and the Common Average Reference (CAR) filter.

A Laplacian spatial filter is comprised of discretized approximations of the sec-

ond spatial derivative of the two-dimensional Gaussian distribution on the scalp surface, and attempts to invert the process that blurred the brain signals detected on the scalp [31]. The approximations are further simplified such that, at each time point t, the weighted sum of the potential s_i of the four nearest or next nearest electrodes is subtracted from the potential s_h at a center electrode for the small and large Laplacian, respectively (see Eq. 2.1,Fig.2.12(a), and Fig. 2.12(b)).

$i \in S_i$

In this equation, the weight $w_{h,i}$ is a function of the distance $d_{h,i}$ between the electrode of interest h and its neighbor i:

$$w_{h,i} = \frac{\frac{1}{d_{h,i}}}{\sum_{i \in S_i} \frac{1}{d_{h,i}}} \tag{2.2}$$

In practice, this filter is often implemented simply by subtracting the average of the four next nearest neighbors (i.e., the weight for each neighbor is -0.25) from the center location.

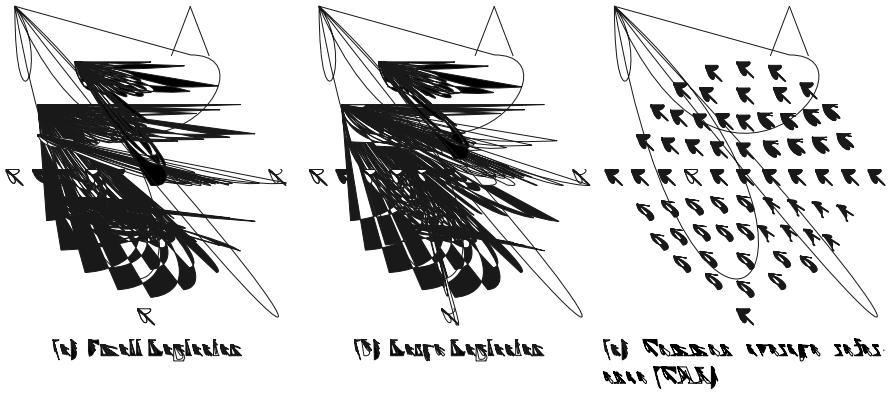

Fig. 2.12 Locations (filled circles) involved in different spatial filters applied to location C_3 (see Fig. 2.13)(open circles)

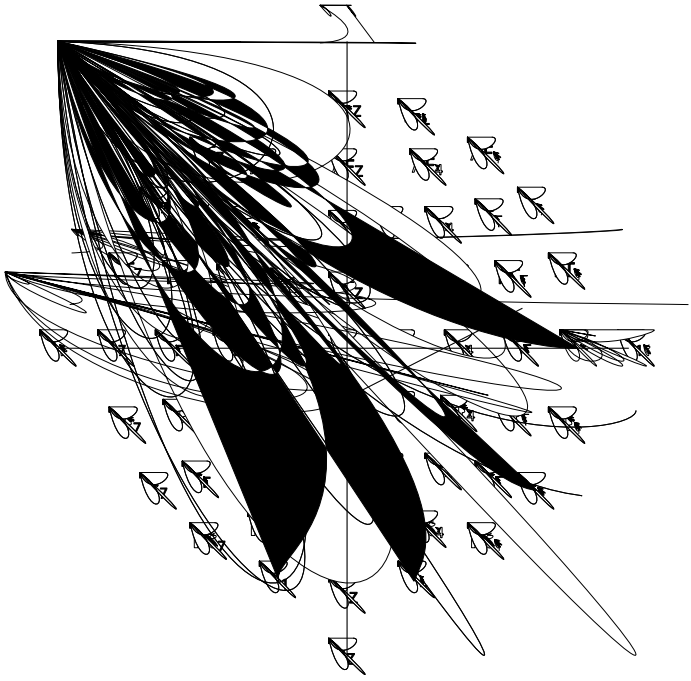

Fig. 2.13 Electrode designations for a 64-channel setup of the extended 10–20 system. (Redrawn from [94])

The Common Average Reference (CAR) filter, another possible spatial high-pass filter, is implemented by re-referencing the potential $s_h(t)$ of each electrode h at each time point t to an estimated reference that is calculated by averaging the signals from all H recorded electrodes (see Eq. 2.3 and Fig. 2.12(c)). In other words, a CAR

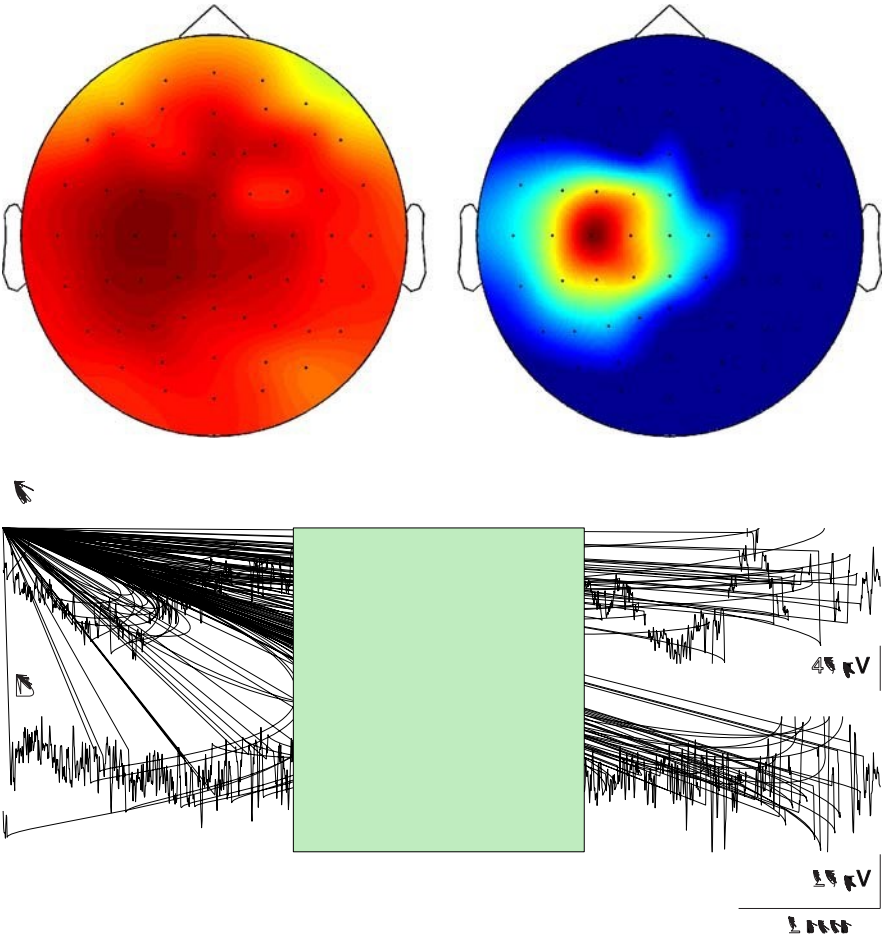

Fig. 2.14 Example of application of a Common Average Reference (CAR) spatial filter. Signals are spatially more specific and better highlight beta rhythm suppression during the period indicated
by the green bar when a CAR filter is applied (B and D) compared to when it is not (A and C)

and subtracts it from the signal $s_h(t)$ at each location. The CAR and Large Laplacian filters have been shown to provide comparable performance [56].

$$s_h(t) = s_h(t) - \frac{1}{H} \sum_{i=1}^{H} s(t)_i \qquad (2.3)$$

Whatever the realization of the spatial filter, its main purposes are to deblur the recorded signals so as to derive a more faithful representation of the sources within the brain, and/or to remove the influence of the reference electrode from the signal.

The example in Fig. 2.14 illustrates results of this operation on signals recorded

using EEG. In this example, the topographies illustrate the effect of a CAR filter on signals in space: in A, the unfiltered signal is spatially broad, whereas in B, the CAR-filtered signal emphasizes spatially local features. (Color indicates the correlation coefficient r calculated between the signal time course at each location (indicated by small dots) and the signal at the location indicated with the white star.) The signal time courses in C and D (which are recorded at the location marked with a star) illustrate the effect of a CAR filter on beta rhythms that are suppressed by right hand movement. The green bar indicates the period that the subject opened and closed her right hand. Beta rhythm oscillations (around 25 Hz) are suppressed during this period. This effect is more pronounced for the CAR-filtered signal in D compared to the unfiltered data in C. Also, application of the CAR filter removes the slow signal fluctuations seen in C. Thus, this example illustrates that the CAR filter removes some of the signal variance that is not related to the hand movement task.

The second and final step of feature extraction is the application of a temporal filter. Its purpose is to project the input signal in a representation (i.e., domain) in which the brain signals that can be modulated by the user are best expressed. The P300 potential is usually extracted in the time domain simply by averaging the brain responses to the different stimuli. Because mu/beta rhythms represent oscillatory activity, they are usually extracted in the frequency domain as described below.

2.4.3 Feature Extraction: Sensorimotor Rhythms

As described, imagined movements have been shown to produce changes in the mu (i.e., 8–12 Hz) or beta (i.e., 18–25 Hz) frequency band. Thus, for the processing of mu/beta rhythm (i.e., sensorimotor) signals, the frequency domain is most often used, although a recent paper suggested a matched filter in the time domain

[38] that better captured the non-sinusoidal components of the mu rhythm. Several methods for the transformation of time domain into the frequency domain have been proposed, such as the Fast Fourier Transform (FFT), wavelet transform, and procedures based on autoregressive parameters. The requirements of BCI systems offer suggestions about which of these methods to select. BCIs are closed-loop systems that should provide feedback many times per second (e.g., typically, at more than 20 Hz) with a minimal group delay. In general, no method can concurrently achieve high resolution in time and frequency. However, the Maximum Entropy Method (MEM) [53], which is based on autoregressive modeling, has a higher temporal resolution (and thus reduced group delay) at a given frequency resolution compared to the FFT and wavelet transforms [53], and is thus advantageous in the context of BCI systems. Whatever its realization, the temporal filter used for mu/beta rhythms transforms time-domain signals $s(t)$ into frequency-domain features $a(n)$.

As an example of its function, Fig. 2.15 illustrates application of the temporal filter to data collected using scalp-recorded EEG while a subject imagined hand movement or rested. CAR-filtered signals at each location were converted into the

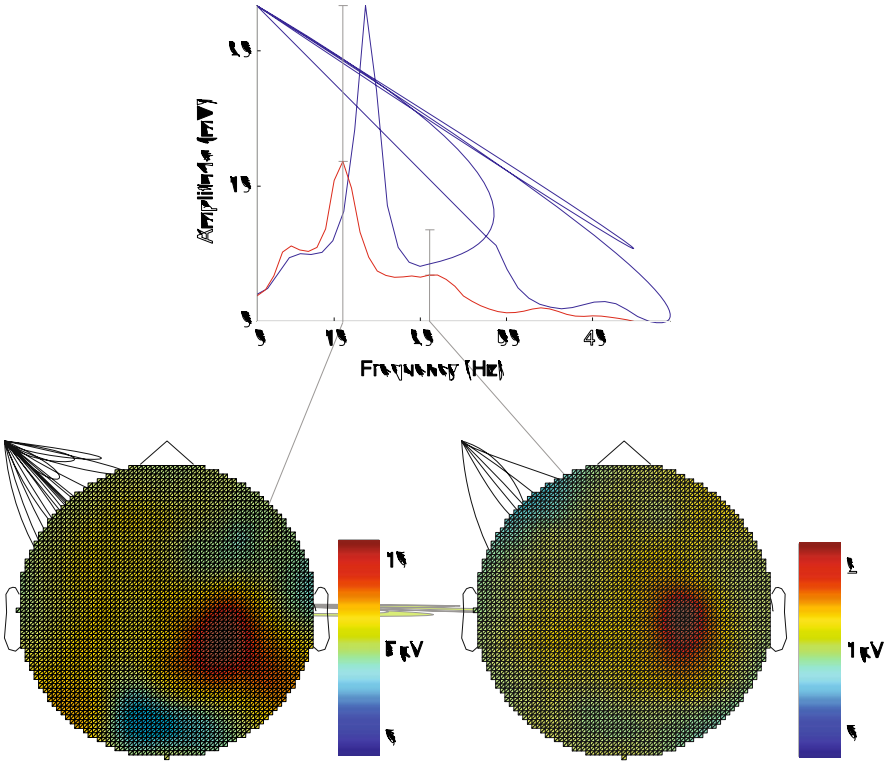

Fig. 2.15 Example analyses of the temporal filter. In this example, EEG was recorded during imagined left hand movement and during rest. The spectrum for rest (blue solid line) is different from that for imagined hand movement (red dashed line). This difference is sharply focused in frequency (see spectra above) and in space (see topographies below) and could be used for BCI control

frequency domain using the MEM algorithm and blocks of 400 ms length. The resulting spectra were averaged across blocks. This produced one average spectrum for each location and for each of the two conditions of imagined movement of the left hand and rest. (The example in Fig. 2.15 illustrates spectra at location C4.) The difference in the spectrum between imagined movement (red dashed line) and rest (blue solid line) is evident and is sharply focused in frequency (around 11 and 22 Hz) and space (over location C4 of right sensorimotor cortex). (While in this figure activity at 22 Hz may simply be a harmonic of activity at 11 Hz, evidence suggests that the relationship between mu and beta rhythms may be more complicated [57].)

In other words, this particular subject can use particular motor imagery to change
the signal amplitude at location C4 and 11/22 Hz and could thus communicate her
intent using this particular type of imagery.

To facilitate understanding of the issues in BCI signal processing, the previous
sections described the first component of BCI signal processing, feature extraction,
which is composed of spatial filtering and temporal filtering. The purpose of feature

extraction is to convert digitized brain signal samples that are recorded at various locations into features (e.g., frequency-domain spectra $a_e(n)$) that express the subject's intent. The second component of BCI signal processing, the translation algorithm, effects this intent by translating these features into device commands. The following section describes a common realization of the translation algorithm.

2.4.4 Translation Algorithm

The second step of BCI signal processing, the translation algorithm, is comprised mainly of a signal translation procedure that converts the set of brain signal features $a_e(n)$ into a set of output signals that control an output device. This translation has been traditionally accomplished using conventional classification/regression procedures. For example, studies have been using linear discriminant analysis [2], neural networks [34, 75], support vector machines [26, 30, 43, 65], and linear regression [54, 55]. To compensate for spontaneous changes in brain signals, the translation algorithm may also include a whitening procedure (e.g., a linear transformation) that produces signals with zero mean and a defined variance such that the output device does not have to account for changes in brain signal characteristics that are not related to the task.

We illustrate the function of a typical approach using an example realization of a translation algorithm using linear regression. Data were derived from the previous example shown in Fig. 2.15. Figure 2.16-A shows the distribution of data samples derived at C4 and 11/22 Hz (i.e., log transformed features $a_1(n)$, $a_2(n)$, respectively). Blue dots show samples that correspond to rest and red dots show samples that correspond to imagined left hand movement. Linear regression determined the coefficients of the linear function that minimized the error between the output of that function ($c(n)$) and arbitrary target values for the two classes (i.e., -1, $+1$).

This procedure derived the coefficients of the linear function that could be used to translate the features into an output signal: $c(n) = 2{,}560a_1(n) + 4{,}582a_2(n)$. The histogram of the values of c(n) calculated for the data from the rest class (blue) is different than that calculated for the data from the imagined hand class (red) (see Fig. 2.16-B), which indicates that the user had some level of control over this particular signal. To quantitatively evaluate this level of user control, we determined the value of r^2, i.e., the fraction of the variance in the output signal c(n) that is associated with the classes. We then applied the same linear function to samples from all electrodes. Figure 2.16-C illustrates that, as expected, the signal difference is sharply focused over right sensorimotor cortex.

In summary, BCI signal processing is accomplished using two components. The first component, feature extraction, extracts brain signal features that reflect the user's intent. The second component, the translation algorithm, translates these signal features into output signals that can control an output device. This translation algorithm has traditionally been realized using a variety of classification/regression approaches. In summary, this chapter described relevant principles of BCI operation

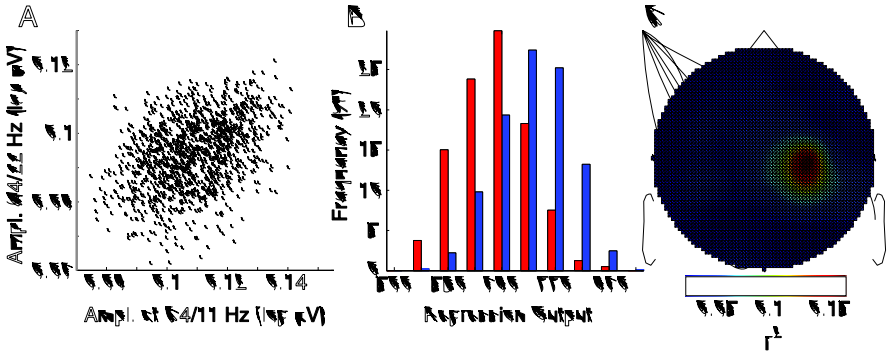

Fig. 2.16 Example of a typical translation algorithm that uses linear regression. A: Distribution
of signal features (i.e., signal amplitudes at C4 and 11/22 Hz for rest (blue dots) and imagined left
hand movement (red dots)). B: Histogram of output values calculated for each of the two classes
using linear regression applied to the two features. C: As expected, the signal difference is focused over right sensorimotor cortex. See text for details

and associated techniques. The next chapter discusses the general concepts of the
BCI2000 platform, and how BCI2000 can implement these techniques.

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Chapter 3
Introducing BCI2000

3.1 Motivation

As described in the previous chapter, many studies over the past two decades have shown that non-muscular communication and control is possible and might serve useful purposes for those who cannot use conventional technologies. At the same time, the performance of this new technology is still modest. The potential value of this new technology will depend largely on the degree to which its performance, i.e., information transfer rate between the user and the BCI system, can be increased.

Many factors determine the performance of a BCI system. These factors include the brain signals measured, the signal processing methods that extract signal features, the algorithms that translate these features into device commands, the output devices that execute these commands, the feedback provided to the user, and the characteristics of the user. Thus, future progress requires systematic well-controlled studies that evaluate and compare alternative signals and combinations of signals, alternative feature extraction methods and translation algorithms, and alternative communication and control applications in different user populations. In consequence, a typical research and development program focused on human BCI research will usually run several studies at the same time, possibly even in different locations, and most often by different personnel.

These requirements imply the need for a software tool that facilitates the implementation of any BCI system, and that facilitates the collaboration of multiple labo-

ratories on algorithm design, experimental design, or data analysis. In other words,
standardized software or procedural mechanisms for development of BCI methods
and their components, for data exchange, and for the appropriate documentation
of relevant configuration parameters are necessary. Furthermore, implementation of
experimental paradigms in other laboratories should be as easy as possible. Unfor-
tunately, the typical BCI system does not readily support such systematic research
and development. While a few systems have attempted to address some aspects of
these issues (e.g., [1, 2, 5, 9]), BCI research has usually consisted of a technical
demonstration of a very specific BCI paradigm, i.e., of a demonstration that a cer-
tain brain signal recorded and measured in a certain way, and translated into control

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commands by a certain algorithm, can control a certain device for one or a few users [15]. Importantly, this situation has not changed by the growing maturization of tools that support rapid prototyping, such as Matlab or LabView. While these tools make it easier to implement one particular BCI paradigm that is run by one person with one particular set of hardware components, such prototyped solutions are typically not robust and/or general enough for use by other people in other environments. In sum, BCI demonstrations have often been based on prototypes that do not support the requirements set forth above.

In recognition of this situation, we set out to develop, test, and disseminate a general-purpose BCI research and development system, called BCI2000, that can facilitate such systematic studies. The goals of the BCI2000 project are (1) to create a system that can facilitate the implementation and collaborative use of any BCI system; (2) to incorporate into this system support for the most commonly used BCI methods; and (3) to disseminate the system and associated documentation to other laboratories. BCI2000 should thus facilitate progress in laboratory and clinical BCI research by reducing the time, effort, and expense of testing new BCI methods, by providing a standardized data format for offline analyses, and by allowing groups lacking high-level software expertise to engage in BCI research.

Over the past nine years, the BCI2000 platform has evolved into a robust software system that can support a wide array of BCI and related studies. To date, BCI2000 has been used to implement BCI methods that can use more than fifteen data acquisition devices, that can make use of sensorimotor rhythms, cortical surface rhythms, slow cortical potentials, and the P300 potential, and that can provide the outputs needed for different kinds of output devices (such as computer cursors, robotic arms, sequential menus, etc.). The continuing grant support for the BCI2000 project also ensures that the system continues to evolve and improve. To facilitate integration in other environments, the BCI2000 software can run on standard PC hardware, and supports a variety of data acquisition devices. Because it is written in C++, it makes

efficient use of computational resources and can satisfy the real-time requirements
of BCI operation.

3.2 The Design of the BCI2000 Platform

3.2.1 A Common Model

BCI2000 is based on a model that can describe any BCI system and that is similar to the one described in [7]. This model (see Fig. 3.1 for a simplified diagram), consists
of four modules that communicate with each other: Source (Data Acquisition and
Storage), Signal Processing, User Application, and Operator Interface. The modules are separate programs that communicate through a TCP/IP-based protocol. This protocol can transmit all information (e.g., signals or variables) needed for operation.
Thus, the protocol does not need to be changed when changes are made in a module.
Brain signals are processed synchronously, in blocks containing a fixed number of

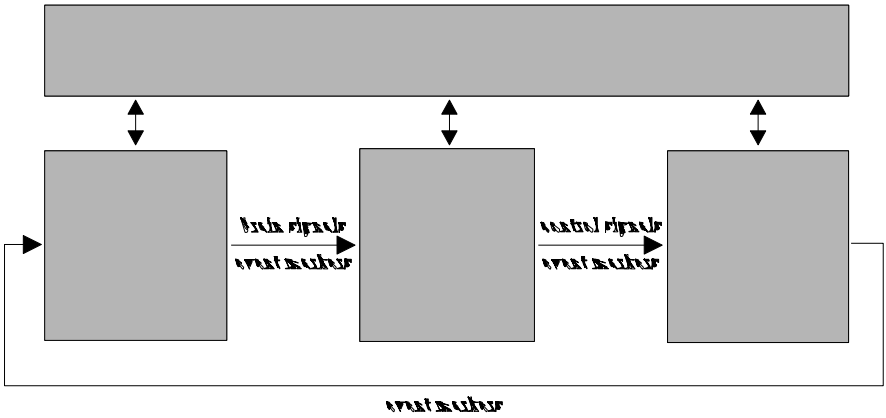

Fig. 3.1 BCI2000 design. BCI2000 consists of four modules: Operator, Source, Signal Processing, and Application. The Operator module acts as a central relay for system configuration and online
presentation of results to the investigator. It also defines onset and offset of operation. During
operation, information (i.e., signals, parameters, or event markers) is communicated from Source
to Signal Processing to User Application and back to Source

samples that are acquired by the Source module. We chose synchronous processing over asynchronous processing, because it makes it more practical to guarantee sys-
tem performance, and it allows for a very generic mechanism to relate the timing
of stimulus presentation to the timing of data acquisition. During system operation,
each time a new block of data is acquired, the Source module sends it to Signal Processing, which extracts signal features, translates those features into control signals, and sends them on to the Application module. Finally, the Application module sends the resulting event markers back to the Source module where they and the raw sig-
nals are stored to disk. The contents of the data file thus allow for full reconstruction
of an experimental session during offline analyses.

The choice of block size is determined by processing resources as well as timing precision considerations. In the BCI2000 on-line system, the duration of a block
corresponds to the temporal resolution of stimulus presentation, e.g., cursor update
rate. This suggests that a small block size is desirable. On the other hand, real-time
operation implies that the average time required for processing a block and commu-
nicating it between modules (roundtrip time) be less than a block's duration. Thus,
processing resources (and network latencies in a distributed system) impose a lower

limit on the block size. A typical configuration, i.e., sampling 16–64 channels at
256 Hz and processing blocks of eight samples each, will result in a feedback up-
date rate of 32 Hz with small output latency. When using data sources that can only
send data at specific block sizes, BCI2000 block size will be further constrained
to multiples of the source's block size. Because the latency between completed ac-
quisition of a data block and stimulus presentation is very small, this synchronous
relationship of data acquisition and stimulus presentation provides a practical and
generic way to associate event markers with brain signal samples.

To maximize interchangeability and independence in BCI2000, we based system design on principles applicable to all BCIs and implemented these principles using current techniques of object-oriented software design.

The TCP/IP-based communication protocol can transmit all information (e.g., signals or variables) needed for operation. Thus, it does not need to be changed when changes are made in a module. The information that passes from one module to another is highly standardized to minimize the dependencies between modules.[1] Each necessary BCI function is placed in the module to which it logically belongs. For example, because each processing cycle is initiated by the acquisition of a block of data samples, Source acts as BCI2000's system clock. Similarly, because feedback control varies with the application (e.g., fixed-length vs. user-paced applications), it is placed in User Application. This principle further reduces interdependence between modules.

The four modules and their communication protocol do not place constraints on the number of signal channels or their sampling rate, the number of system parameters or event markers, the complexity of signal processing, the timing of operation, or the number of signals that control the output device. Thus, these factors are limited only by the capacities of the hardware used.

3.2.2 Source Module and File Format

The Source module acquires brain signals and passes calibrated signal samples on to the Signal Processing module. The Source module consists of a data acquisition component, and a data storage component that implements the native BCI2000 file format, as well as EDF, which is a data format popular in sleep research [6], and GDF, a variant of EDF designed for BCI applications [11]. The data acquisition component has a number of implementations. The implementations for the g.USBamp and g.MOBIlab devices from `g.tec` are directly supported by the BCI2000 development team, i.e., they are part of the BCI2000 core distribution. A number of implementations for hardware from other manufacturers (i.e., BioSemi, BrainProducts, Cleveland Medical Devices, Data Translation, Electrical Geodesics, Measurement Computing, National Instruments, Neuroscan, OpenEEG, Tucker-Davis Technologies) have been provided by the BCI2000 user community.

The BCI2000 file format consists of an ASCII header that defines all parame-

ters used for this particular experimental session, followed by binary signal sample
and event marker values. The file format can accommodate any number of signal

[1]User applications might employ distinctive stimuli to evoke brain responses (such as the P300
speller included with BCI2000). Because these BCI paradigms depend on the brain's responses
to the stimuli, their User Applications cannot be interchanged with ones that do not provide the
stimuli. In other situations, online adaptations occurring in the Signal Processing module depend on the feedback provided to the user. Thus, a certain degree of module interdependence is sometimes
unavoidable.

channels, system parameters, or event markers, and thus can accommodate any experimental protocol. It supports 16- and 32-bit integer formats as well as a 32-bit floating point format.

3.2.3 Signal Processing Module

The Signal Processing module converts signals from the brain into signals that control an output device. In the current BCI2000 implementations, this conversion is done in two stages, feature extraction and translation, and realized using a chain of signal filters, each of which transforms an input signal into an output signal. The individual signal filters are designed to be independent of each other and can thus be combined or interchanged without affecting others.

The first stage, feature extraction, is currently comprised of two filters. The first filter can implement any linear spatial filtering operation by calculating a matrix multiplication of the input signals with a spatial filtering matrix. The second filter is called “temporal filter.” The current BCI2000 core distribution comes with three different variations of this temporal filter: autoregressive spectral estimation; spectral estimation based on the Fast Fourier Transform (FFT); and a filter that averages evoked responses (e.g., P300s). The second stage, feature translation, translates the extracted signal features into device-independent control signals. This is done by two filters. The first applies a linear classifier, and the second filter normalizes the output signals such that they have zero mean and a specific value range. The output of this procedure is the output of the Signal Processing module.

3.2.4 User Application Module

The User Application module receives control signals from Signal Processing and uses them to drive an application. In most present-day BCIs, the user application is presented visually on a computer screen and consists of the selection of targets, letters, or icons.

Existing User Application modules in BCI2000 implement very capable versions of popular feedback paradigms: a three-dimensional cursor movement paradigm (Cursor Task); a matrix spelling application based on P300 evoked potentials (P3 Speller); and presentation of auditory and visual stimuli with optional feedback of evoked potential classification results (Stimulus Presentation). Figure 3.2-A–C shows the display to the user for these three applications, respectively.

3.2.5 Operator Module

The Operator module provides the investigator with a graphical interface that displays current system parameters and real-time analysis results (e.g., frequency

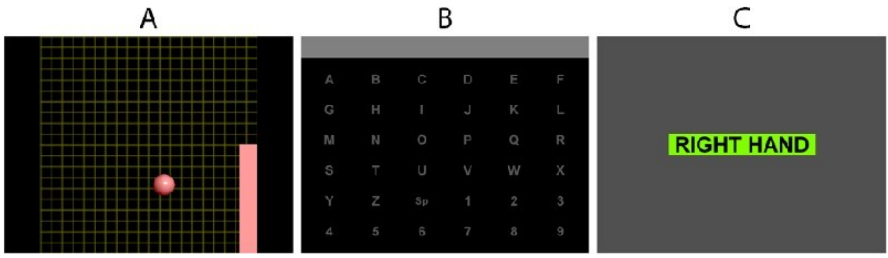

Fig. 3.2 Displays for the three BCI2000 User Applications. A: Cursor movement to a variable number of targets (i.e., Cursor Task). B: A spelling application based on P300 evoked potentials
(i.e., P3 Speller). C: Auditory/visual stimulation program (i.e., Stimulus Presentation). In A,the cursor moves from a programmable location towards one of N programmable targets. In B,rows
and columns of the matrix flash in a block-randomized fashion. In C, a series of programmable
stimuli are presented in sequence

spectra) communicated to it from other modules. It allows the investigator to start,
stop, suspend, resume, or reconfigure system operation. In a typical BCI2000 con-
figuration, user feedback is displayed on one monitor, and the Operator module's
graphical interface (i.e., the interface to the investigator) is displayed on a second
monitor.

3.2.6 System Variables

BCI2000 incorporates three types of system variables: parameters, event markers,
and signals. System parameters are those variables that do not change throughout
a data file (i.e., during a specified period of online operation). In contrast, event
markers record events that occur during operation and that can change from one
data sample to the next. The inclusion of all event markers in the data file allows
full offline reconstruction and analysis of the experimental session. Each module
has access to these event markers, and can modify and/or simply monitor them.
Finally, system signals are functions of the user's brain signals that are received and modified by the modules.

Each module can request that the Operator module create any number of system

parameters (of different data types such as numbers, vectors, matrices, or strings) or
event markers (each 1–16 bits long). For example, the Source module might request a parameter that defines the signal's sampling rate. This parameter is constant during
some defined period of online operation, is available to all other modules, and is
automatically recorded in the data file. Similarly, a Signal Processing filter designed to detect artifacts (such as those created by muscle movements) might request an
event marker with which to mark artifacts in the signal, and an Application module
might request an event marker to record stimulus conditions. These different system variables are automatically communicated and supported throughout the system, are
aligned with signal samples, and stored.

3.3 BCI2000 Advantages

The generic concepts described above are of particular advantage for large research and development programs. For example, because of the standardized protocol between modules, different realizations of the different modules can usually be mixed with other modules. For example, different Source modules (providing support for different data acquisition devices) can be utilized with the same signal processing routines and feedback modalities. This greatly facilitates the development of the complete experiments, or parts of experiments, in different locations and environments.

Because the graphical interface to the investigator in the Operator program is generated dynamically based on the parameterization requirements of the particular data acquisition device, signal processing routines, and experimental protocol, the same Operator program (and not one for each possible combination of these routines) can be used in different environments or for different experiments.

Because the data format adapts to the particular set of event markers requested by the different modules, introduction of a new event marker (e.g., to report an artifact detected by a new signal processing routine) only involves a small change in the component that realizes the new signal processing component. The data format is automatically adapted by the system and all BCI2000 components interacting with the data format (e.g., file viewer, data export into Matlab) are able to work with these new types of data without any change.

In summary, the BCI2000 platform implements a number of general concepts that are applicable to a wide array of different experiments. Thus, it provides optimum benefits to interactive and collaborative situations that involve a number of experiments, locations, and personnel.

3.4 System Requirements and Real-Time Processing

As a run-time environment, the current implementation of BCI2000 requires Mi-

crosoft Windows 2000 or a more recent Windows-based operating system, any
recent desktop or laptop computer, and one of the data acquisition devices that
BCI2000 supports.

A BCI system must acquire and process brain signals (potentially from many
channels at high sampling rates) and respond with appropriate output within a short
time period (i.e., latency) with minimal variation (i.e., latency jitter). To give an im-
pression of the timing performance of BCI2000 in actual online operation, we eval-
uated system performance in two different signal processing/task configurations.
The hardware platform used for this test was a Mac Pro workstation with two 2.8
GHz quad-core Intel Xeon processors, 6 GB RAM, NVIDIA 8800GT (512 MB)
video card, running Windows XP. Feedback was provided using a CRT monitor with
100 Hz update. This system acquired data from 32 channels at 1200 Hz using two
g.tec g.USBamp amplifier/digitizer systems and a block size of 100 ms, i.e., signal
display, signal processing, and feedback were updated 10 times per second. In the

Cursor Task signal processing/task configuration, BCI2000 extracted signal features from all 32 channels using an autoregressive method to calculate voltage spectra, and provided three-dimensional feedback using the Cursor Task application. In the P3 Speller signal processing/task configuration, BCI2000 extracted and classified average waveforms from all 32 channels, and implemented the row/column speller paradigm described in [4].

In the Cursor Task configuration, the mean processing latency of the BCI2000-based system was 20 ms. In other words, BCI2000 calculated the spectra of 32 channels, and translated the spectra into a three-dimensional movement signal, in 20 ms. The mean processing latency for the P3 Speller configuration was 8 ms. For both configurations, the average video output latency (i.e., the latency between the end of processing and update on the video screen) was 6.23 ms. Thus, while MS-Windows is not a real-time operating system and thus does not guarantee specific timing of events, in each test case, system latency easily satisfied the real-time requirements of BCI operation. Furthermore, processor load was sufficiently low to guarantee reliable operation. This indicates that BCI2000 could have handled even higher sampling rates, larger numbers of channels, or more complex signal processing methods. Please see [13] for a comprehensive description of the complete timing evaluation.

3.5 BCI2000 Implementations and Their Impact

We tested the adaptability and online performance of BCI2000 by using it to implement two very different BCI designs, each of which had previously been implemented only by its own highly specialized software/hardware system. In each case, the BCI2000 implementation required minimal effort to set up and yielded results comparable to those reported for the dedicated system. Furthermore, in each case the standard BCI data storage format readily supported the appropriate offline data

analyses.

To implement mu/beta rhythm cursor control, we configured BCI2000 with autoregressive spectral estimation and the cursor task. In our configuration of this task, a target appeared in one of four possible locations along the right edge of the screen. Then, a cursor appeared at the left edge and moved from left to right at a constant rate with its vertical movement controlled by the power in a mu or beta rhythm frequency band at a location over sensorimotor cortex (see [8] for further detail). To date, several hundred people have used this system extensively (i.e., 4–300 sessions each). Figure 3.3-A illustrates the spectral and topographical features of the mu/beta rhythm control that users achieve and that allows them to move the cursor to the designated target.

To implement the P300-based BCI paradigm described by Donchin and his colleagues [3, 4], we configured BCI2000 with the temporal filter that averages evoked potentials and the P3 Speller application. As illustrated in Fig. 3.3-B, the results are similar to those reported for the original hardware/software P300 BCI system [4]. As described earlier in this book, many peer-reviewed publications have used BCI2000 using these or other configurations.

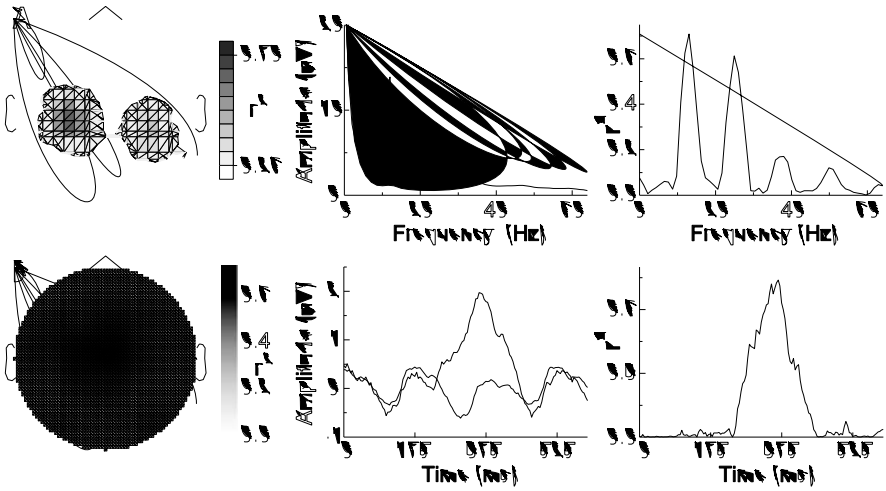

Fig. 3.3 BCI2000 implementations of common BCI designs (from [10]). A: Mu/beta rhythm control of cursor movement. Left: Topographical distribution on the scalp (nose on top) of control (measured as r^2 (the proportion of the single-trial variance that is due to target position)), calculated between top and bottom target positions for a 3-Hz band centered at 12 Hz. Center: Voltage spectra for a location over left sensorimotor cortex (i.e., C3 (see [12])) for top (dashed line) and bottom (solid line) t argets.Right: Corresponding r^2 spectrum for top versus bottom targets. The user's control is sharply focused over sensorimotor cortex and in the mu- and beta-rhythm frequency bands. The data are comparable to those of earlier studies that used a specialized hardware/software system (e.g., [14]). B: P300 control of a spelling program. Left: Topographical distribution of the P300 potential at 340 ms after stimuli, measured as r^2 (calculated from averages of 15 stimuli) for stimuli including versus not including the desired character. Center: T hetime courses at the vertex of the voltages for stimuli including (solid line) or not including (dashed line) the desired character. Right: Corresponding r^2 time course. The data are comparable to those of earlier studies using a dedicated hardware/software system (see [3, 4]). Stimulus rate was 5.7 Hz (i.e., one every 175 ms). See text and references for other details

This chapter provided an introductory overview of the basic concepts of BCI2000, and how these concepts can be used to realize different BCI implementations. The following chapter provides an introductory hands-on tour through the BCI2000 platform.

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Chapter 4
Tour of BCI2000

In this chapter, we present a general overview of BCI2000 to demonstrate important features of the software and other concepts that are relevant to any BCI session. We will cover methods for starting the BCI2000 software; give a brief tour of the user interface; describe setting, saving, and loading parameters; and retrieving data offline.

4.1 Starting BCI2000

There are two methods for starting the BCI2000 software system. BCI2000 consists of four programs (i.e., modules) that need to be started up in a certain order. These modules handle acquisition of brain signals (i.e., Source module), processing of these brain signals (i.e., Signal Processing module), user feedback (i.e., User Application module), and the interface to the investigator (i.e., Operator module), respectively. These four modules can be started using the batch files in the `BCI2000/batch` directory. Alternatively, BCI2000 comes with a program called `BCI2000Launcher` that allows you to manage module startup using a graphical user interface.

4.1.1 Batch Files

A group of pre-configured batch files are located in the `BCI2000/batch` directory. In general, these may need to be modified to correspond with the specific modules

used for a particular experiment, although in most instances the appropriate config-
uration already exists if g.tec amplifiers are used. In any batch file, the four mod-
ules are started with the `start` command, starting with the Operator, i.e., `start`
`operat.exe`. Next, the Source, Signal Processing, and Application modules are started, with the IP address of the Operator passed as an argument. In most cases,
this is on the local machine, which has an address of `127.0.0.1`.

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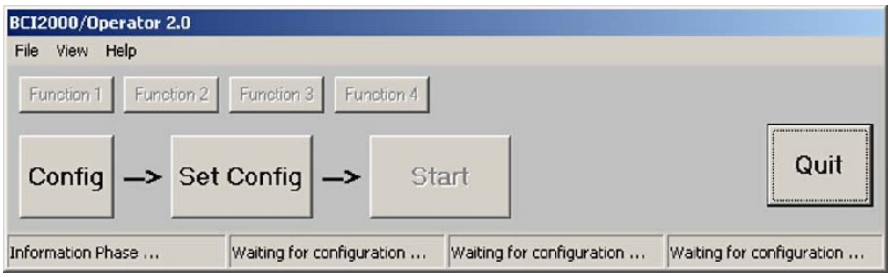

Fig. 4.1 The Operator main window

4.1.2 BCI2000 Launcher

The BCI2000Launcher program provides a convenient user interface for organizing BCI2000 applications and parameter files. The Source, Signal Processing, Application, and Operator modules are selected from a list, multiple parameter files can be passed to BCI2000 and loaded automatically, and all are launched simultaneously, replacing the need for multiple batch files.

To start the tour, perform the following steps:

Start BCI2000

1. Navigate to the `BCI2000/batch` directory.
2. Double-click the file `CursorTask_SignalGenerator.bat`. This will launch the modules required for a simulation of a BCI session based on sensorimotor rhythms.

The Operator window will appear, with all of the modules connected (Fig. 4.1).

4.2 Getting Help

When the main Operator window appears, choose BCI2000 Help from the Help menu. The Operator module's help page will be opened in a web browser window. On the left side of the help page, a navigation menu provides access to available help.

Further information about BCI2000 can be found on the BCI2000 Wiki, which is located at http://doc.bci2000.org/wiki/; and users can ask questions in the BCI2000

forums, which is located at http://bbs.bci2000.org. In these forums, the BCI2000
developers and other users can answer questions that are not covered in this book.

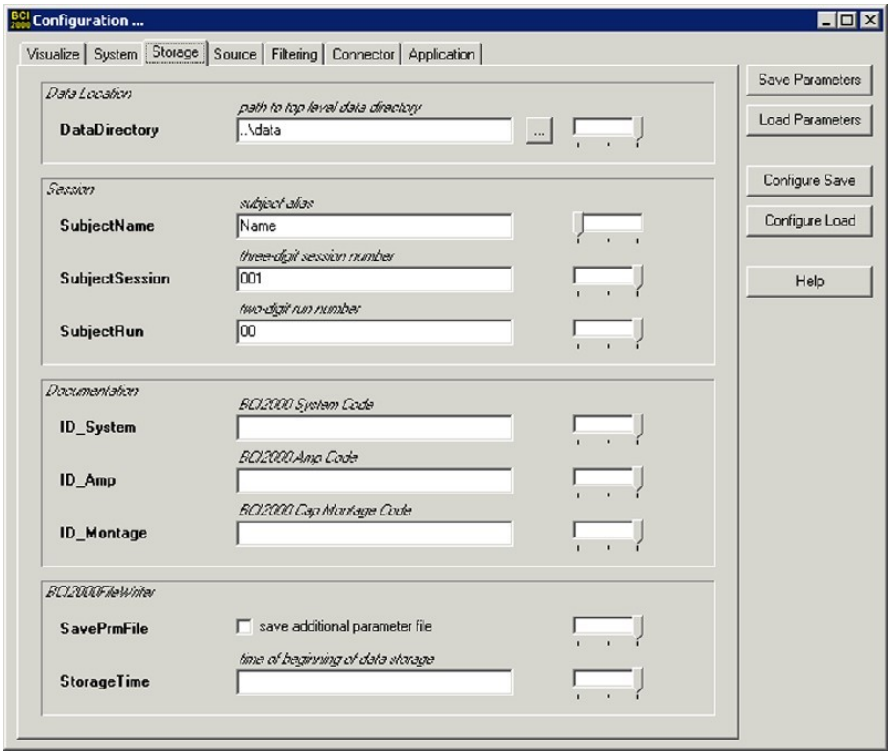

Fig. 4.2 The BCI2000 Configuration dialog

4.3 Configuring BCI2000

BCI2000 has an extensive set of configuration parameters, which are dependent on
the particular modules being used, and must be set for each session. This section
provides a review of configuring BCI2000, and loading and saving your settings for future use.

Enter the BCI2000 Configuration Dialog

1. Press the Config button in the Operator window.

4.3.1 Module Settings

When you press Config, the BCI2000 Configuration window appears (Fig. 4.2). Across the top of this window, you will see a series of several tabs. Each tab con-
tains a different group of parameters; these parameters are specified by the (Source,
Signal Processing, and User Application) modules that are being used. There will

always be Visualize, System, Storage, Source, Connector, and Application tabs;
the Filtering tab will almost always be present, unless the `DummySignalProcessing` module is used. Additional tabs may appear as well, depending on the
modules that are running.

Within each tab, parameters are organized further into smaller groups that are
dependent on their function. For example, the Filtering tab might contain groups
of parameters organized by SpatialFiltering, Classification, and Normalization, among others. Detailed information about all parameters can be found in Chap. 10.

4.3.2 Parameter Files

The configuration for a particular experiment implemented in BCI2000 is stored in
parameter files. Before performing an experiment, you will typically load a parameter file that contains subject-specific as well as general configuration information.

Load a Parameter File

1. Press the Config button in the Operator window to enter the Configuration dialog.
2. Press Load Parameters on the right side of the window.
3. Navigate to `BCI2000/parms/`, and open `parms/fragments/amplifiers/SignalGenerator.prm`.
4. Press Load Parameters again, and open `parms/mu_tutorial/MuFeedback.prm`.

Parameter files may contain all parameters needed for a particular experiment, or only a subset. In the latter case, we call those parameter files parameter fragments.
Each fragment can contain information that can be reused across sessions and subjects, e.g., a fragment might contain only those settings that pertain to the cursor
task and that can be applied to any subject; another fragment might contain settings
for a particular amplifier; and yet another fragment might contain information for
an individual subject. Therefore, several fragments may be used together to define
the configuration of a particular experiment.

4.3.3 Parameter Help

It is possible to obtain information about each parameter within the Configuration
window. To do so, press the Help button on the right side of the Configuration win-

dow. This will turn the cursor into a question mark. If you click on a parameter label, a web browser will appear with a help page that describes that parameter.

Parameter Help Example

1. Press the Storage tab.
2. Press the Help button on the right side of the Configuration window.
3. Use the mouse to click on the SubjectName parameter.
4. Information about the SubjectName parameter is shown.

4.4 Important Parameters

The BCI2000 framework will always include a number of parameters, regardless of the type of experiment. In this section, the parameters that define the location and
file naming conventions of the data file will be configured.

Setting the Storage Parameters

1. Open the Configuration window, and navigate to the Storage tab.
2. Under DataDirectory, the value corresponds to the base directory in which all acquired data will be saved.
3. Relative or absolute paths can be used for this value. Relative paths are relative to the `BCI2000/prog/` directory. In this case, `../data` is specified, so data will be saved in `BCI2000/data/`.
4. The SubjectName parameter should be set to a value such as TEST, or the subject's initials. Set this to `test` for this demo.
5. The parameter SubjectSession should be set to a three-digit value corresponding to the number of sessions that a particular subject has participated in. Set
this to `001` for this demo.
6. The parameter SubjectRun should be set to `00` at the start of a new session.
This number will increment automatically with each run, i.e., existing data files will never be overwritten if the SubjectRun value equals that of an existing file.

4.5 Applying Parameters

Once you have defined the experimental parameters, they must be applied to
BCI2000.

Applying Parameters

1. Close the Configuration window by pressing the "X" button located on the top-right corner of the window. This will accept your parameter changes.
2. In the main Operator window, click Set Config. This will apply the changes in configuration.
3. The Operator module will send the configuration parameters to the other
BCI2000 modules, which in turn validate the values to ensure that they are
consistent.
4. If all parameter values are consistent, the signal source window will appear and display the brain signals.
5. The signal source window can be moved and resized; this position is preserved across BCI2000 sessions.

In a true BCI session, in which you will be recording signals from the brain, you

will use the signal source window to assess the quality of the recorded signals. In this

simulation session, you will notice a change in the simulated brain signal when you move your mouse. We will use these signal changes to control a cursor on the screen.

When you right-click on the signal window, you will notice a context menu with particular display options, such as increasing/decreasing the number of channels displayed, choosing display colors, applying filters to the signal, etc. Please see Sect. 10.1.5 for more details.

4.6 Starting a Run

In this demonstration, you will simulate a real cursor movement experiment by modulating artificial brain signals with your mouse.

Performing a Session

1. Perform all of the steps described above.
2. Press Set Config to apply parameters.
3. You will see the simulated brain signals on the screen. Channels 1 and 2 contain 10 Hz sinusoidal signals whose amplitudes are modulated by the position of the mouse.
4. To increase or decrease the amplitude of channel 1, move the mouse up and down on the screen, respectively. To increase or decrease the amplitude of channel 2, move the mouse left and right on the screen, respectively.
5. Press the Start button to start the experiment, i.e., a simulated feedback session.
6. During the session, you will see a cursor that moves from left to right on the screen at a constant rate.
7. You will also see one of two targets on the screen. Your goal is to direct the cursor to the target.
8. The vertical velocity is controlled by the amplitude of channel 1. To move the cursor up, increase the amplitude, and to move it down, decrease the amplitude.
9. When the run has completed, the Suspend button will change back to Start.

The period during which the cursor moves from left to right is called a trial. During operation, there will be a number of successive trials. Many trials make up one experimental run, where each run usually lasts about 3–5 minutes. When the run is finished, BCI2000 will stop operation on its own, and the Start button will change to

Resume. At that time, the corresponding data file has been closed. Clicking Resume each time, you may add as many runs to the current session as you like. All runs within a session will be stored as separate files in that session's data directory.

BCI2000 contains a component that adapts itself to the brain signal's characteristics (i.e., its mean value and its amount of variation). This component needs to observe the signal for a few trials until it has appropriately adapted to those characteristics. This means that initially you may not feel a correspondence between your actions and the cursor. As you proceed through a few trials, you will note that control becomes more accurate. Also, it is important that you place the mouse cursor in

a center position at the beginning of each trial to give you enough space to move in
the required direction. Likewise, when a real subject controls the cursor using brain signals, the system will need a few trials to adapt to the subject's general signal characteristics. (It may take the subject quite some time to learn how to actually control
that signal.) When you have acquired one or more runs, you may quit BCI2000.

4.6.1 Data Storage

All data acquired during a run are stored in a single BCI2000 data file that
has the extension `.dat`. This data file contains all brain signals, all parameters you just defined, and all event markers (i.e., state values) that encode important events during each run. The location and name of the data file depends on the Storage parameters. The file naming convention based on these
parameters is: `<DataDirectory>/<SubjectName>S<SubjectSession>/<SubjectName>S<SubjectSession>R<SubjectRun>.dat`, e.g., `data/testS001/testS001R00.dat`.

4.7 Retrieving Data Offline

4.7.1 Reviewing Brain Signals and Event Markers

Several methods for retrieving data offline for viewing or analysis exist. The
`BCI2000Viewer` program allows you to review brain activity and associated event markers.

Viewing Brain Signals

1. In Windows Explorer, navigate to the BCI2000Viewer directory i.e., `BCI2000/tools/BCI2000Viewer`, and double-click the `BCI2000Viewer.exe` file to start the program.
2. In BCI2000Viewer (see Fig. 4.3), open the data file that was created for this
   demo session, located at `BCI2000/data/testS001/testS001R00.dat`.

Every BCI2000 data file contains several experiment-specific event marker channels that are stored with every signal sample.

View Event Markers

1. The right side of the BCI2000Viewer program contains a list of channels and event markers, which are called states in BCI2000.

2. To view particular event markers, click the box next to the corresponding state
   name.
3. Check the TargetCode, ResultCode, and Feedback checkboxes.

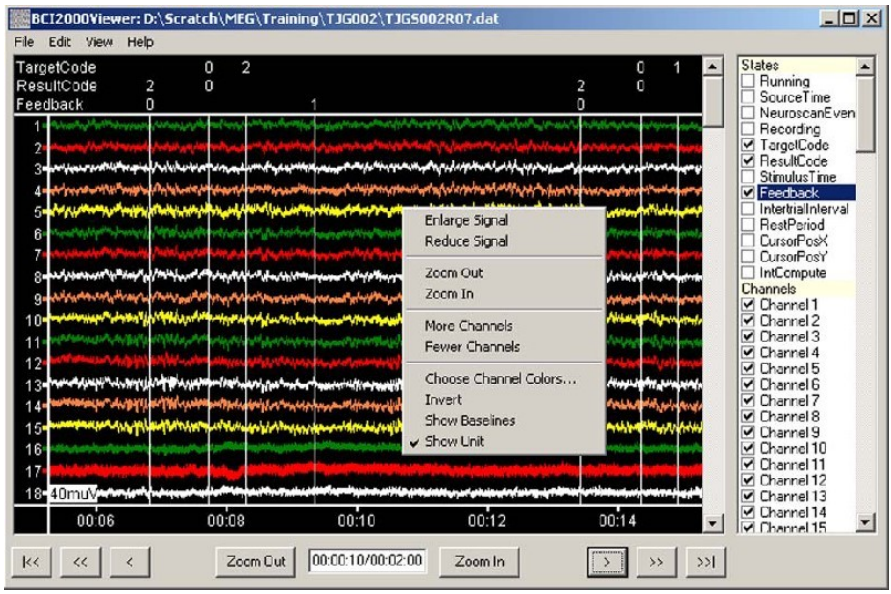

Fig. 4.3 The BCI2000Viewer program

The values of these event markers will be displayed on top of the signal traces.

Whenever TargetCode changes from 0, a target was displayed during the recording.

Whenever ResultCode changes from 0, a target has been hit by the cursor. A Feedback value of 1 indicates that the feedback cursor was visible. In data analysis, this state information makes it possible to determine trial structure and data labels. It is important to note here that the number, names, and meaning of the state variables are not predefined, but rather depend on the experiment, i.e., the particular collection of Source, Signal Processing, and User Application modules used for that experiment. Thus, you can easily write BCI2000 code that would add several new state variables with new meaning. These state variables would automatically be included in the data file and appear in BCI2000Viewer.

Help on state variables is available as well. Right-click the TargetCode entry in the top right corner of the BCI2000Viewer window and choose Help on the TargetCode state variable from the context menu. A browser window will open up and will show a help page that describes that variable.

4.7.2 Viewing Parameters with BCI2000FileInfo

In addition to state information, each data file contains the full set of parame-
ters and their values that defined recording of this particular experimental run.
You may view those parameters, or even save them to a parameter file in orig-

inal or modified form, using the `BCI2000FileInfo` program that is located in `tools/BCI2000FileInfo`.

To open a `.dat` file in `BCI2000FileInfo`, drag and drop it onto the program symbol or into the program's main window. Then, click Show Parameters. This will open a parameter configuration dialog identical to the one you know from the Operator module.

4.7.3 Interactions with External Software

BCI2000 provides several software components that support interactions with external software, in particular with Matlab, FieldTrip (through a contribution by Robert Oostenveld) and Python (through a contribution by Jeremy Hill). These components can be used to load data from BCI2000 data files to analyze data offline, or to implement and test new signal processing techniques or feedback paradigms online.
BCI2000 also provides a simple network-based interface (called the AppConnector protocol) that any external software can use to interact with BCI2000 in real time.
A selection of these methods is covered in Chap. 6.

4.8 Overview of Additional Application Modules

BCI2000 contains several core application modules that are capable of providing multiple feedback methods, including visual and audio presentation. You have already been introduced to the cursor task; the remaining core applications are briefly covered in the following sections.

4.8.1 Stimulus Presentation

In addition to the cursor task, BCI2000 comes with a multi-purpose stimulus presentation program. This module has many of the features of dedicated programs like Presentation or e-Prime. The difference between these dedicated programs and stimulus presentation in BCI2000 is that BCI2000 makes it very easy to integrate

that stimulus presentation with real-time data acquisition, processing, and feedback.

In BCI research, the BCI2000 Stimulus Presentation module is often used for an initial mu rhythm session. Because this module has good timing characteristics, it is also suitable for a wide range of psychophysiological experiments such as the ERP experiments described here. Furthermore, it can be used in conjunction with the P3 Signal Processing module (which can average and classify ERPs) to provide real-time feedback to evoked potentials.

To try the Stimulus Presentation module, start BCI2000 using the `StimulusPresentation_SignalGenerator.bat` file in the `batch` directory. Then,

click Config, and load the configuration file at `parms/examples/StimulusPresentation_SignalGenerator.prm`. Navigate to the Storage tab and enter a subject ID into the SubjectName parameter. Run the experiment by clicking Set Config and Start. (Note: The goal here is simply to introduce you to the Stimulus Presentation module. We will not discuss all possibilities of this module here. Please see Sect. 10.8.2 for more information.) When you are done, locate the resulting data file at `data/<SubjectName>001/<SubjectName>S001R01.dat`, and open it using `BCI2000FileViewer`, similar to what you did for the simulated cursor movement session earlier in this tour. In `BCI2000FileViewer`'s main window, check the StimulusCode checkbox to display the StimulusCode state variable. During presentation of a stimulus, the StimulusCode state is set to an ordinal number that corresponds to which stimulus was presented. In data analysis, this information may then be used to segment data into epochs and to group epochs according to different stimuli.

4.8.2 P300 Speller

As part of its core distribution, BCI2000 also comes with the `P300Speller` module. The P300 Speller implements a BCI that uses evoked responses to select items from a rectangular matrix, a paradigm originally described by Farwell and Donchin.

To calibrate the P300 Speller for an individual subject, it is first operated in a "copy spelling" mode, which prompts the user to pay attention to pre-defined letters in sequence. Start `batch/P3Speller_SignalGenerator.bat`, click Config, and load `parms/examples/P3Speller_CopySpelling.prm`. Close the configuration window, then click Set Config and Start to view copy spelling in action.
In this example, the simulated EEG will simulate evoked responses to the correct stimuli (i.e., correct row and column). This makes it possible to test signal classification and spelling functionality. In this example, spelled letters will correspond to the letters to be copied.

In real experiments, such as those described later in this book, the experimenter would use data from the copy spelling session to calibrate the P300 Speller. Once

calibrated, the purpose of the P300 Speller is to enable the user to choose letters from the matrix, i.e., “free spelling,” without a pre-defined letter sequence. The speller also supports multiple matrices (or “menus”), graphical icons, and auditory stimuli (i.e., wave files). To perform a “free spelling” demo with multiple menus, click Config and load `parms/examples/P3Speller_Menus.prm`. Then close the configuration window, click Set Config, and Start. In simulation mode, you can select a matrix element by clicking it with the mouse. Actual P300 classification is done by averaging several responses to a particular stimulus. Thus, clicking an item will not immediately select it. Rather, mouse selection will override classification once the number of averaging epochs is reached. This will take a few seconds.

4.9 Where to Go from Here

In this tour, we covered several basic aspects of BCI2000 theory and operation.
This included a brief introduction to different BCI2000 modules that support BCI operation using sensorimotor rhythms and evoked responses. The following chapter provides tutorials for implementing working BCI systems using each of these two
brain signals.

Chapter 5
User Tutorials

5.1 General System Configuration

Prior to running experiments, the computer and display system must be configured
for both the experimenter and the subject. This tutorial assumes that you will be
using a dual-monitor setup as shown below, with the experimenter of the sessions
operating on monitor 1, and the subject watching on monitor 2. This system config-
uration is typical for most BCI experiments, and can be used for the Cursor move-
ment, P300 Speller [1], or Stimulus Presentation tasks.

Configure a Dual-Monitor Setup

1. Open Display Properties by right clicking on an empty portion of the desktop and clicking Properties.
2. Navigate to the Settings tab.
3. You will see a representation of the position and geometry of both monitors.
   Ensure that monitor 2 is enabled by clicking on it, and clicking the check box labeled Extend my Windows desktop to this monitor, and hitting Apply.
4. First, make sure that monitor 2 is aligned with the top of monitor 1 by clicking and dragging it to the correct position (Fig. 5.1).
5. Make note of the width of monitor 1 and the resolution of monitor 2. In this example, monitor 1 is 2,048 pixels wide, and monitor 2 is 1,024 pixels wide by 768 pixels tall (Fig. 5.2).
6. Close the display windows.

5.2 Virtual Cursor Movement with the Sensorimotor Rhythms

A BCI cursor movement experiment is generally done in three steps: (1) obtaining

sensorimotor rhythm parameters in a screening session; (2) analyzing the screening data and picking the best EEG features; (3) configuring BCI2000 with the chosen

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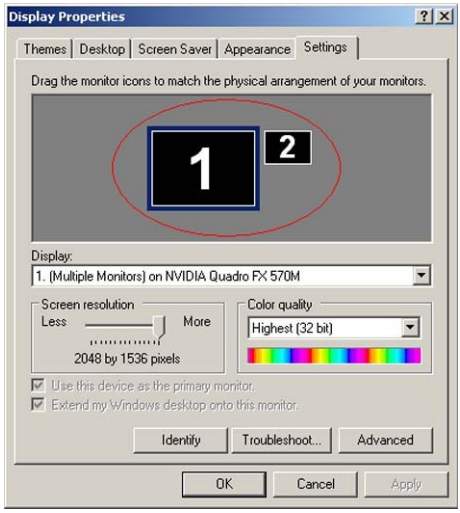
Fig. 5.1 Here we need to make sure that monitor 2 is aligned along the top with monitor 1, and that monitor 2 is to the right of monitor 1



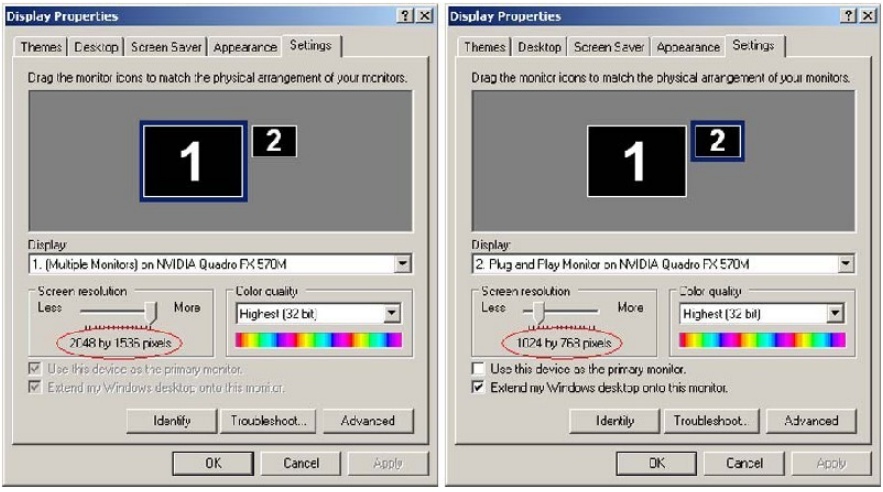


Fig. 5.2 What we need to make a note of is the Width of monitor 1,andtheWidth and Height of monitor 2. In this example we see that monitor 1 is 2,048 pixels wide, and monitor 2 is 1,024
pixels wide by 768 pixels tall

features; and (4) running an online session in which the subject moves a computer cursor. The following four sections will cover these four steps.

5.2.1 Obtaining Sensorimotor Rhythm Parameters in an Initial Session

Although the basic properties of mu/beta rhythms are identical for all humans, spatial patterns and exact frequencies are different from person to person. Thus, it is necessary to obtain these subject-specific parameters prior to any feedback experiments, i.e., to calibrate the BCI system using data acquired from an initial session.

In this initial session, the subject is instructed to imagine hand and/or foot movements in response to visual cues. To identify a subject's mu/beta rhythm, offline analyses then determine the frequency and location whose activity changes the most across conditions (e.g., hand imagery and rest). These analyses result in spectra calculated at different locations or in topographical plots at particular frequencies.

First, you need to connect the sensors to the amplifier system. For EEG, you may want to review Sect. 2.3 regarding electrode placement, etc. Then, you need to configure BCI2000 for this session as described below.

Configure the Mu/Beta Rhythm Session

1. Connect your amplifier to the computer, and turn it on.*
2. Run the `batch/StimulusPresentation_<amplifier>.bat` file. For example, if you are using the g.MOBIlab amplifier, you would run `batch/StimulusPresentation_gMOBIlab.bat`.
3. Press the Config button to bring up the BCI2000 Configuration window.
4. Press Load Parameters and load `parms/fragments/amplifiers/<amplifier>.prm`.
5. Next, load `parms/mu_tutorial/InitialMuSession.prm`.
6. In the Storage tab, set SubjectName to the subject's initials, set SubjectSession to `001`, and SubjectRun to `01`.
7. In the Source tab, set ChannelNames to the electrode names corresponding to each channel. In this example, `F3 F4 T7 C3 Cz C4 T8 Pz` are used, based on their respective positions in the 10–20 convention.

8. If using a g.MOBIlab amplifier, set COM port to the port name that you found earlier, e.g., `COM8:`.
9. In the Application tab, set WindowWidth to the width of the subject's display monitor, and WindowHeight to the height (`1024` and `768`, respectively, in this example).
10. Set the WindowLeft to the width of the experimenter's monitor. In this example, this would be `2048`.

Configure the Mu/Beta Rhythm Session (continued)

11. Take note of the Sequence field. This field contains four single-digit numbers separated by one space. These numbers correspond to the presentation frequency of each row in the Stimuli matrix. Initially it will be 1 1 1 1, indicating that stimuli 1 through 4 should each be presented an equal number of times; the first number corresponds to the left hand, the second is the right hand, the third for both hands, the fourth for both feet. Therefore, setting this field to 2 1 0 1 will call for the subject to move the left hand twice as often as the right or both feet, and will never call for both hands to be moved.
12. Press Save Parameters, and save the file with a descriptive name. You can use this parameter file as the basis for future sessions.

* If your amplifier is from the gMOBIlab family, you will need to make a note of the port it is connected to. In order to determine that port, go to the Windows Start Menu, and choose Start → Control Panel → System → Hardware → Device Manager → Ports (COM & LPT). If you are using a different amplifier, please check the amplifier documentation, and/or the amplifier-specific sections in Chaps. 10 and 11.

During the initial session, the subject's screen will either be blank, or displaying an arrow pointing up, down, left, or right. The instructions for the subject for each of these periods are as follows:

Instructions to the Subject

1. When a left or right arrow is displayed, imagine movement of the respective hand. The imagined movement should be continuous opening and closing of the hand (e.g., squeezing a tennis ball) at a rate of about one opening and closing per second.
2. When an up arrow is displayed, imagine simultaneous movement of both hands. This should be the same kind of movement as described for a single hand.
3. When a down arrow is displayed, imagine movements of both feet. The movement should be similar to the one described for hands, i.e., imagine opening and closing your feet as if you could use them to grip an object.
4. When you see a blank screen, relax and stop any movement imagery.

5.2.2 Performing the Initial Sensorimotor Rhythm Session

To start an experimental run, click Run in the operator window. Each run gathers
20 data points, or “trials,” that differentiate between moving the left hand, the right
hand, both hands, and both feet. Ideally, there should be 100 trials, meaning that
five runs are suggested. This is done as five separate runs instead of one to allow
the subject a chance between each run to rest, blink, swallow, speak, or have some
water if so desired.

5.2.3 Analyzing the Initial Sensorimotor Rhythm Session

To identify the parameters (i.e., frequency and location) of a subject's mu/beta rhythm, we will determine how different the EEG signal amplitude is at different frequencies and locations between rest and movement imagery, or between different types of imaginations. BCI2000 provides an "Offline Analysis" tool for this purpose.

5.2.3.1 Generating Feature Maps

The first step in these analyses is to separate data into amplitudes at individual frequencies and locations. For our purposes, these amplitudes are called features, and their correspondence with the subject's imagination will be plotted as a so-called feature map. From a feature map, it is possible to determine those frequencies and locations whose amplitude is maximally correlated with the subject's task, i.e., those features that are most different between two conditions. These features will subsequently be used to provide feedback in a BCI experiment.

To generate a feature map from the initial session's data, perform the following steps:

Generating a Feature Map

1. Start the BCI2000 "Offline Analysis" tool. If you have a version of Matlab installed, run `tools/OfflineAnalysis/OfflineAnalysis.bat`. Otherwise, download the MATLAB Component Runtime (MCR) from `http://www.bci2000.org/downloads/bin/MCRInstaller.exe` and install it. Then, run `tools/OfflineAnalysis/OfflineAnalysisWin.exe` to begin analyzing your data.
2. In the Analysis Domain field, choose Frequency.
3. In the Acquisition Type field, choose EEG.
4. As a Spatial Filter, choose Common Average Reference (CAR).
5. Enter `states.StimulusBegin == 1` into the Trial Change Condition field.
6. Into the field labeled Target Condition 1, enter `(states.StimulusCode == 0)`.
7. Enter the word `Rest` into the field labeled Target Condition Label 1.
8. Similarly, enter `(states.StimulusCode == 2)` into the Target Condition 2 field, and `Right Hand` into Target Condition Label 2.
9. Click the Add button located besides the Data Files field. A file chooser dialog

will appear; navigate to `data/mu/<Subject>001`, and select all .dat files that you just collected (use your keyboard's ctrl button to click-select multiple files), then click the dialog's Open button.

10. Click Generate Plots, and wait for the feature map to appear.

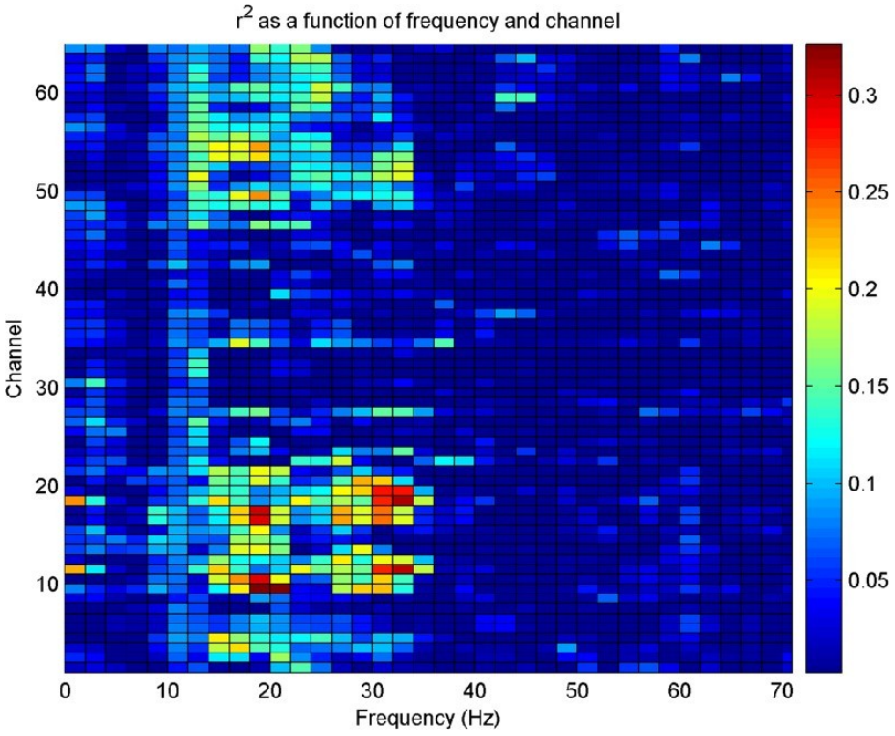


Fig. 5.3 An example EEG feature map

Once the computation is complete, you will see a feature map similar to Fig. 5.3. In that plot, the horizontal axis corresponds to frequencies, and the vertical axis corresponds to individual channels. Color codes represent r^2 values, which are numbers between 0 and 1. r^2 values provide a measure for the amount to which a particular EEG feature (i.e., amplitude at a particular frequency and location) is influenced by the subject's task (e.g., hand vs. foot imagery).

Typically, there will be clusters of large r^2 values in the feature map. The initial step to configure the online system is to determine which brain signal feature differed the most between two particular tasks. At the same time, it is important to verify whether the properties of that feature are consistent with the mu/beta rhythm's known properties. This verification is necessary to avoid misconfiguration of the system to use EEG artifacts, other noise, or random effects, rather than features originating within the brain.

To verify candidate features, pick the four largest r^2 values from the feature map between 8 and 36 Hz, and read off their frequencies and channels. The program's "Data Cursor" tool (Data Cursor from the Tools menu) may be helpful for this.

Then, enter the channel numbers you read off the feature map in the analysis pro-
gram’s Spectra Channels field, and enter the frequencies in the field for the Topo
Frequencies. Then, click the Generate Plots button.

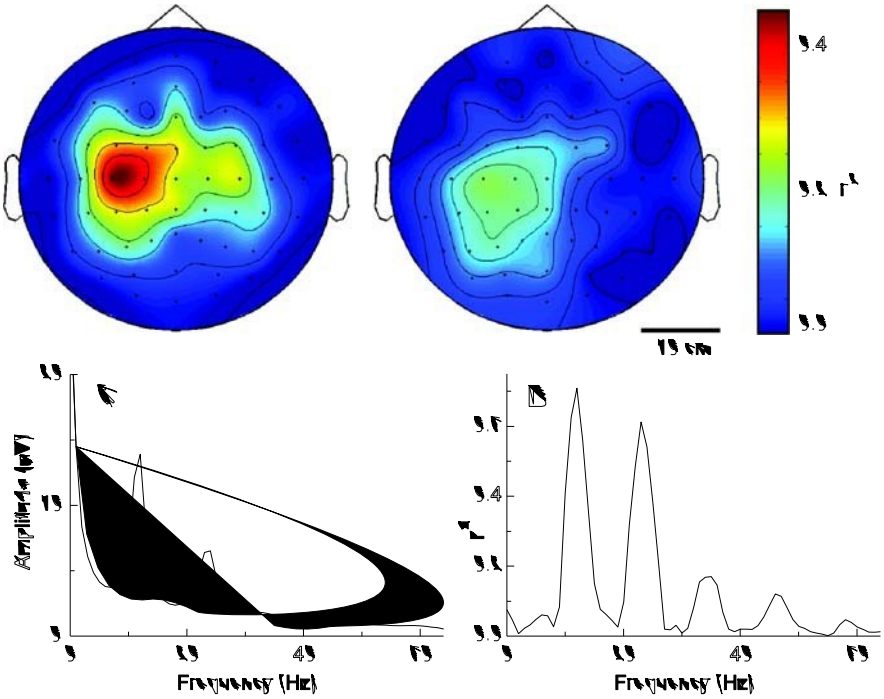


Fig. 5.4 Scalp topographies of activation during movements (modified from [2]). A, B: Topographical distribution on the scalp of the difference (measured as r^2, or the proportion of the single-trial variance that is due to the task), calculated for actual (A) and imagined (B) right-hand movements and rest for a 3-Hz band centered at 12 Hz. C: Example voltage spectra for a different subject and a location over left sensorimotor cortex (i.e., C3 (see [3])) for comparing rest (dashed line) and imagery (solid line). D: Corresponding r^2 spectrum for rest vs. imagery. Signal modulations are focused over sensorimotor cortex and in the mu- and beta-rhythm frequency bands

The generated topography plots display the spatial distribution of r^2 values similar to those in Fig. 5.4-A/B. In particular, there should be a clear maximum of r^2 values over the left motor cortex as shown in subfigure A for actual movements and B for imagined movements. The generated spectra plots display amplitude distributions and r^2 values across a range of frequencies. Ideally, they should appear similar to those in Fig. 5.4-C/D.

5.2.3.2 Analyzing Remaining Conditions

Up to now, you performed an analysis that determined how brain activity is related

to imagined movements of the right hand. In order to choose the most useful chan-
nel and frequency for online feedback, perform similar analyses for the remaining
conditions:

Remaining Conditions

1. In the analysis program's Target Condition 2 field, enter `states.StimulusCode == 1`, and `Left Hand` into Target Condition Label 2.
2. Make sure the Overwrite existing plots check box is unchecked.
3. Click Generate Plots to create a feature map for imagined movement of the left hand.
4. As previously, pick the four largest r^2 values, and compute spectra and topographies for their channels and frequencies.
5. Results should somewhat resemble that derived for the right hand, except that the colored activity changes should appear over the right and not the left motor cortex.
6. Repeat the analysis for conditions `states.StimulusCode == 3` (Both Hands), and `states.StimulusCode == 4` (Both Feet).
7. For the `both hands` condition, the result should resemble a combination of `left hand` and `right hand` results.
8. For `both feet`, modulated activity should be centered around electrode Cz.

5.2.3.3 Picking Optimal Features

You should now have identified a number of candidates of channel/frequency pairs for each condition, and you should have some impression how physiologically plausible these are. In particular, we would like to see results that at least somewhat resemble those shown in Fig. 5.4, i.e., frequencies with the highest r^2 value between 8 and 36 Hz, and locations with the highest r^2 value at appropriate locations (e.g., C3 for right hand movement/imagery; C4 for left hand movement/imagery; C3 and C4 for both hands; and Cz for both feet).

5.2.4 Configuring Online Feedback

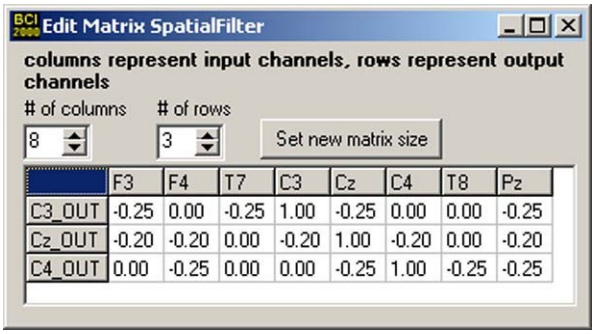
After picking a desired target feature (i.e., desired frequency and location), we can now configure BCI2000 to extract and use that feature.

Configuring BCI2000

1. Run the `batch/CursorTask_<amplifier>.bat` file. In the example, we are using the gMOBIlab amplifier, so we would run `batch/CursorTask_gMOBIlab.bat`.
2. Press the Config button to bring up the BCI2000 Configuration window.
3. Press Load Parameters, and first load the parameter file created and saved for

the screening session. This will re-load many parameters that can be re-used.

4. Next, press Load Parameters and load: `parms/fragments/amplifiers/<amplifier>.prm`, then `parms/mu_tutorial/MuFeedback.prm`.



	F3	F4	T7	C3	Cz	C4	T8	Pz
C3_OUT	-0.25	0.00	-0.25	1.00	-0.25	0.00	0.00	-0.25
Cz_OUT	-0.20	-0.20	0.00	-0.20	1.00	-0.20	0.00	-0.20
C4_OUT	0.00	-0.25	0.00	0.00	-0.25	1.00	-0.25	-0.25

Fig. 5.5 Spatial Filter configuration

Configuring BCI2000 (continued)

5. In Storage, change SubjectName to the subject's initials.
6. Set SubjectSession to `002` and SubjectRun to `01`.
7. Press Save Parameters, and save to an appropriate file.

This file is now the base parameter file for your amplifier when configuring your system to user-specific settings for the cursor task portion of future sessions.

5.2.4.1 Configuring the Spatial Filter

The Spatial Filter computes a weighted combination of the incoming data from the electrodes based on their placement on the scalp of the subject. Because we are targeting specific areas of the brain to monitor, we use a spatial filter that allows the program to identify when the electrode of interest is activating specifically. This is done by subtracting the average of the surrounding electrodes' data from the electrode of interest. For example, as seen in Fig. 5.5, in which the incoming signals are in the columns and in which the rows represent the output of the spatial filter, the output channel `C3_OUT` is the data from electrode `C3` minus one-quarter of each of electrodes F3, T7, `Cz`, and Pz. Such a filter is called a "Laplacian filter." Please note that you should change the column labels depending on the montage and/or channel order you used.

Spatial Filter Configuration

1. Enter the Configuration window.
2. Press the Filtering tab.
3. Set the SpatialFilterType to Full.
4. Press the Edit Matrix button next to the SpatialFilter parameter.

5. Set # of Columns to 8, and # of Rows to 3.
6. Right-click the empty top-left matrix entry, and choose “Edit labels” from the
context menu.

Spatial Filter Configuration (continued)

7. For column headings, enter channel names in the same order as the ChannelNames parameter.
8. Set the table values as shown in Fig. 5.5, adjusting the columns depending on the montage you used.
9. Close out of the Matrix editing window.

5.2.4.2 Configuring the Classifier

After defining an appropriate filter, you have to tell BCI2000 which location and frequency should be used for the feedback session. This is done as follows:

Linear Classifier Configuration

1. In the Configuration window, select Edit Matrix next to the Classifier parameter in the Filtering tab.
2. Set Number of columns to 4, and Number of rows to 1 (or the number of features that you wish to use). Click Set new matrix size to apply your changes.
3. In the first column (of the first row), labeled input channel, enter the code for the channel you would like to use, e.g., `C3_0UT`, `C4_0UT`,or`Cz_0UT`.
4. If both hands are used, set Number of rows to 2, and click Set new matrix size. Enter `C3_0UT` in row 1, column 1, and enter `C4_0UT` in row 2, column 1.
5. In the second column, labeled input element (bin), enter the frequency of your feature, immediately followed with Hz, e.g., 12Hz.
6. In the third column, enter the value 2. This value defines the output control signal that the resulting signal should go in. In the cursor movement task, control signals 1–3 correspond to horizontal, vertical, and depth movement, respectively.
7. In the fourth column, enter `-1` (minus one) as the weight.
8. Finally, save your configuration in a parameter file wherever you find appropriate.

It is important to note that this tutorial gives a functioning, but only simple, example. BCI2000 could be configured to use more complex spatial filters, perform different frequency estimation, or more complex classification. Please see Sect. 10.6 for more details on the configuration of the signal processing component.

5.2.5 Performing a Sensorimotor Rhythm Feedback Session

5.2.5.1 Starting the Session

To perform a mu/beta rhythm feedback session, start the BCI2000 system using the appropriate batch file at `batch/CursorTask_<amplifier>.bat`, or the link to

that file which you created on the desktop. Then, load the configuration file that you saved for this subject previously by pressing Config, and then Load Parameters.
Click Set Config to view the EEG signal, and prepare the subject for EEG recording as you did in the initial session.

5.2.5.2 Instructions to the Subject

When the subject is ready for EEG acquisition, it is time to brief the subject about the experimental task. Suggested instructions for the experimenter and subject are listed below.

Instructions to the Subject

1. After pressing the Set Config button, a screen with a yellow grid is initially presented.
2. Instruct the subject to minimize: (1) contraction of the muscles of the face/head, and swallowing; (2) eye blinks and eye movements; and (3) other motion.
3. As soon as the subject is ready and the EEG traces have stabilized, the investigator will start acquisition.
4. After pressing Start, there will be a brief pause of about 2 s (or equal to the PreRunDuration parameter).
5. A target will appear on the right edge of the screen for about one second. This is called the pre-feedback phase.
6. A cursor will appear on the left edge of the screen, and begins to move horizontally towards the right edge of the screen. Its vertical position is controlled by the EEG features that were defined in the previous step.
7. The subject's task is to move the cursor vertically so that it hits the target when the cursor hits the right edge of the screen. The time needed for the cursor to move from the left to the right edge of the screen should be approximately three seconds.
8. If the subject successfully hits the target, the target changes its color. Otherwise, no change occurs. In either case, this period lasts one second.
9. The screen will then turn black for one second. This indicates the end of the trial. After this one-second period, the next trial starts.

When a target is presented, the subject should imagine the type of movement associated with the channel-frequency features chosen for feedback. For example, when the largest r^2 value was associated with left hand movement imagination in

the offline analysis, ask the subject to use this imagination to control the direction of cursor movement. Imagined movement will move the cursor upward on the screen, and relaxing will move it downward.

Explicitly specifying a type of imagination to control cursor movement will help the subject achieve initial cursor control. Once the subject has become more proficient with the task, motor imagery typically becomes less important. In this situation, it is not uncommon that subjects report that they just “imagine moving the cursor.”

Provided that subjects are asked to minimize artifacts, he/she should be further assisted in these efforts by providing a comfortable chair and a dimly lit room. The experimenter must carefully monitor the EEG and alert the subject in the case he/she has forgotten some of the instructions. When the experimenter is sure that his/her instructions have been well understood, the recording session may start.

Click the Start button to start the feedback experiment. During the experiment, the subject's performance is written into a log window on the experimenter's screen, and recorded into a log file that is saved to disk in the session directory. The experimenter should minimize noise in the room and not disturb the subject.

5.2.5.3 Monitoring the Recording

After recording has started, the experimenter may feel the temptation to leave the subject alone during the run since most of the experimental activities are automated in BCI2000. However, the experimenter has several important tasks during the experiment.

Experimental Tasks for the Researcher

1. Fill in a run sheet to report information that is not automatically recorded by BCI2000 and that will later help when data are analyzed (e.g., subject did not seem to understand the instructions in the first run, instructions to the subject for a particular run, disturbances, etc.).
2. Monitor the EEG signal to verify the quality of the recording (e.g., no electrode contact failure, muscular, ocular, or motion artifacts, etc.).
3. Notify the subject if he/she is producing artifacts, keep the subject alert if getting drowsy, give the subject feedback about his/her performance so that interest, alertness, and attention is kept high.

The run sheet is extremely important, in that it documents important information or observations relevant to data analysis. In general, all information that could be important for data analysis and that is not explicitly documented elsewhere, need to be included. For example, the sampling rate is documented in BCI2000 parameters,

while the name of the experimenter may not be documented elsewhere. Examples
of such important details are comments about the subject's performance during a
particular experimental run (e.g., subject getting sleepy, interruption at 12:34p), or
about the experimental setup (e.g., used electrode cap #3, montage #2, distance of
subject to screen 70 cm, etc.).

5.2.5.4 Multiple Sessions

Once a run has ended, BCI2000 goes into suspended state. Further runs will be
added to the session when you click Resume. After the session has finished, you may

want to save auto-adjusted parameters for the next session. Use Save Parameters from the configuration window to do this.

Alternatively, the Load Parameters dialog allows you to choose a data file rather than a parameter file, and thus use the configuration contained in a previous session's data file for the next session. However, parameters contained in a data file reflect the state at the beginning of the recording, so changes during a session's last run cannot be recovered that way.

When beginning the next session, don't forget to increment the SessionNumber parameter on the Storage tab. Otherwise, new runs will be added to the previous session's directory. As a safety net, BCI2000 will never overwrite existing data files, and it documents date and time in the StorageTime parameter. This allows the experimenter to later separate data files into runs even if the SessionNumber parameter has not been increased.

After each session, it is recommended that you analyze the recorded data in the same way as you did for the initial session. This allows you to track and adapt to signal changes in the subject's parameters that may occur in the course of learning.

5.2.5.5 Important Remarks

One critical element of such experiments is that they need to be consistent and rigorous. For example, a typical session will consist of a number (e.g., 4–8) of 3-minute experimental runs. Unless there is an obvious technical problem (e.g., the cursor always immediately jumps to the bottom of the screen, which would point to a misconfiguration of BCI2000), do not change any of the parameters (such as locations, frequencies, etc.) across these runs. When doing offline analyses, always strive to collect at least four runs with the exact same configuration. Because there is so much variability in the subject's performance and in the EEG, it is likely that you will oth-

erwise not be able to derive meaningful results or conclusions. You may find that,
for example, for three consecutive sessions the subject's best frequency is 12 Hz and not 10 Hz as initially configured. In this case, you could make this small adaptation to the parameters, and have a reasonable chance that it will actually improve the
subject's performance.

5.3 P300 BCI Tutorial

The previous sections described the configuration and use of BCI2000 for sensori-
motor (i.e., mu/beta) rhythms. The present chapter will describe a similar process
for the P300 evoked potential. Just as with the mu rhythm, successful P300 BCI
experiments require several steps that include obtaining initial data in a calibration
session, selecting the best features related to the task, and finally performing the
P300 spelling session. This section will cover all of these steps.

5.3.1 General System Configuration

The system should be configured for two monitors, as described in Sect. 5.1.

5.3.2 Obtaining P300 Parameters in the Calibration Session

Although the basic properties of the P300 evoked potential are the same for all individuals, the response's latency, width, and spatial pattern varies, and adaptation to individual parameters improves accuracy. Thus, it is necessary to obtain these individual parameters prior to performing spelling experiments.

Configure the P300 Spelling Session

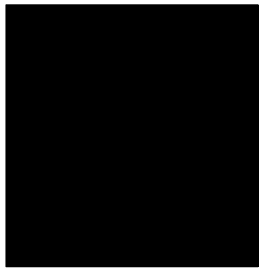
1. Connect your amplifier to the computer, and turn it on.*
2. Run the `batch/P3Speller_<amplifier>.bat` file. For example, if you are using the g.MOBIlab amplifier, you would run `batch/P3Speller_gMOBIlab.bat`.
3. Press the Config button to bring up the BCI2000 Configuration window.
4. Press Load Parameters and load `parms/fragments/amplifiers/<amplifier>.prm`.
5. Next, load `parms/p3_tutorial/InitialP3Session.prm`.
6. In the Storage tab, set SubjectName to the subject's initials, set SubjectSession to `001`, and SubjectRun to `01`.
7. In the Source tab, set ChannelNames to the electrode names corresponding to each channel. In this example, `F3 F4 T7 C3 Cz C4 T8 Pz` are used, based on their respective positions in the 10–20 convention.
8. If using a g.MOBIlab amplifier, set COM port to the port name that you found earlier.
9. If a gMOBIlab is used, set the COMport parameter found earlier.
10. In the Application tab, set WindowWidth to the width of the subject's display monitor, and WindowHeight to the height (`1024` and `768`, respectively, in this example).
11. Set the WindowLeft to the width of the experimenter's monitor. In this example, this would be `2048`.
12. Press Save Parameters, and save the file as you deem fit.

* If your amplifier is from the gMOBIlab family, you will need to make a note of the port it is connected to. In order to determine that port, go to the Windows Start Menu, and choose Start → Settings → Control Panel → System → Hardware → Device Manager → Ports (COM & LPT).

This file is now the base parameter file for your amplifier when configuring the

system to user-specific settings.

Fig. 5.6 P300 Speller matrix



5.3.2.1 Experimental Design

During the calibration session, the subject is asked to successively focus on different characters in a matrix (Fig. 5.6). During each run, the subject is asked to focus on the next letter in the word he or she is spelling, as the rows and columns flash randomly and successively so that sometimes the flashing corresponds to the column or row containing the target character and, more often, it will not. As the subject counts the number of times the next letter in the word flashes, a P300 response is generated.
The purpose of the calibration session is to identify those features that discriminate between the desired and undesired rows and columns.

After the first few runs are collected, we will again use the “Offline Analysis” tool to determine which features (in this case, signals at a particular location and time after the stimulus) correspond to the row or column of the desired character.

5.3.2.2 Performing the Calibration Session

While the P300 response shares basic properties for all individuals, some specific details vary from person to person, such as latency, width, and spatial pattern. By adapting the basic parameters to the specifics associated with each individual subject, we can improve his or her accuracy drastically.

P300 Calibration

1. Start BCI2000 by running `batch/P3Speller_<amplifier>.bat`.
2. Press Config, and load the baseline parameters for copy spelling that you made earlier.
3. In the Storage tab, set SubjectName to the subject’s initials, SubjectSession to `001`, and SubjectRun to `01`.
4. Press the Application tab.
5. Make sure that InterpretMode is set to `copy mode`, and DisplayResults

(directly below InterpretMode) is unchecked.

6. Find the TextToSpell field. This should be set to THE, and you will be changing it after each run.
7. Press Set Config to apply this configuration.

P300 Calibration (continued)

8. Request that the subject sit in a relaxed position, and that the subject not move or speak during the runs.
9. Turning off or dimming the lights can improve subject focus and performance.
10. Showing the brain signal window on the subject's screen while describing EEG artifacts can assist in describing how artifact-generating behavior can be detrimental to the data.
11. Press Start to show the flashing character matrix, and describe what the subject is expected to do.
12. After you have explained the procedure, click Suspend to stop the process.
13. Delete that run of data, found at `data/P300/<Subject Initials>001/<Subject Initials>S001R01.dat`.
14. Press Start to record the run.
15. Once it has finished automatically, click Config and change the TextToSpell field in the Application tab to `QUICK`.
16. Press SetConfig.
17. Press Start to record the run.
18. Once it has finished automatically, click Config and change the TextToSpell field in the Application tab to `BROWN`.
19. Press SetConfig and then Start to record the run.
20. Once it has finished automatically, click Config and change the TextToSpell field in the Application tab to `FOX`.
21. Press SetConfig and Start to record the run.
22. Once this recording has finished, close BCI2000 and locate the saved data files for analysis.

5.3.3 Analyzing the Calibration Session with "Offline Analysis"

5.3.3.1 "Offline Analysis" Tool

We will now use the BCI2000 "Offline Analysis" tool to analyze the subject's initial session.

Offline Analysis

1. Run `tools/OfflineAnalysis/OfflineAnalysis.bat`.
2. In the Analysis Domain field, choose `Time(P300)`.
3. In the Acquisition Type field, choose `EEG`.
4. As a Spatial Filter, choose `Common Average Reference (CAR)`.
5. Set the Trial Change Condition field to `states.StimulusBegin == 1`.
6. Set Target Condition 1 to: `(states.StimulusCode >0) & (states.StimulusType == 1)`.

Offline Analysis (continued)

7. Enter `Attended Stimuli` for Target Condition Label 1. “Attended Stimuli” refers to the letter or character the person is counting the flashes of, and triggers when the correct stimulus is shown.
8. Set Target Condition 2 to: `(states.StimulusCode >0) & (states.StimulusType == 0)`.
9. Enter `Unattended Stimuli` for Target Condition Label 2. “Unattended stimulus” refers to the letters or characters the person is not counting the flashes of, and triggers when an incorrect stimulus is shown.
10. Click the Add button by the Data Files field.
11. In this new dialog, select all of the data files taken during this configuration session, and click Open.
12. Click Generate Plots and wait for the feature map to appear.

When this is complete, you will see a feature map similar to that in Fig. 5.7. In this plot, the vertical axis corresponds to the different locations, while the horizontal axis corresponds to the time after the stimulus. As before, the color shows the value of r^2 calculated between desired and not desired brain responses (i.e., responses to correct vs. incorrect row/columns). Red colors indicate a high correlation of the brain signal amplitude at the time/location with flashing of the desired row/column, and blue colors indicate little correlation. We are interested in finding large r^2 values between 200 and 550 ms.

Selecting Features

1. Pick the four points with the largest r^2 values between these times and record their time points and channels. The plot’s Data Cursor tool (Tools Menu → Data Cursor) allows for discrete selection of time points.
2. In the example shown in Fig. 5.7, the four best data points have r^2 values `0.02218`, `0.02179`, `0.00328`, and `0.003`; occur at times `388.7ms`, `392.6ms`, `384.8ms`, and `365.2ms` respectively; and all four are detected by channel six.
3. To produce topographies and time course plots, you would enter `6` into the Waveform Channels field and `388.7, 392.6, 384.8, 365.2` into the Topo Times field.

4. Click Generate Plots to create the feature map again with a set of four graphs that show the correlation of the brain responses with the task category (i.e., desired vs. undesired row/column).
5. As seen in Fig. 5.8, the attended-stimulus reaction will typically be stronger than for the unattended stimuli, but in some cases the reverse is true. If the 'unattended' curve is larger than the 'attended' curve then make a note of this before moving on. The waveform seen here is similar to the others generated, only one is shown here for simplicity.

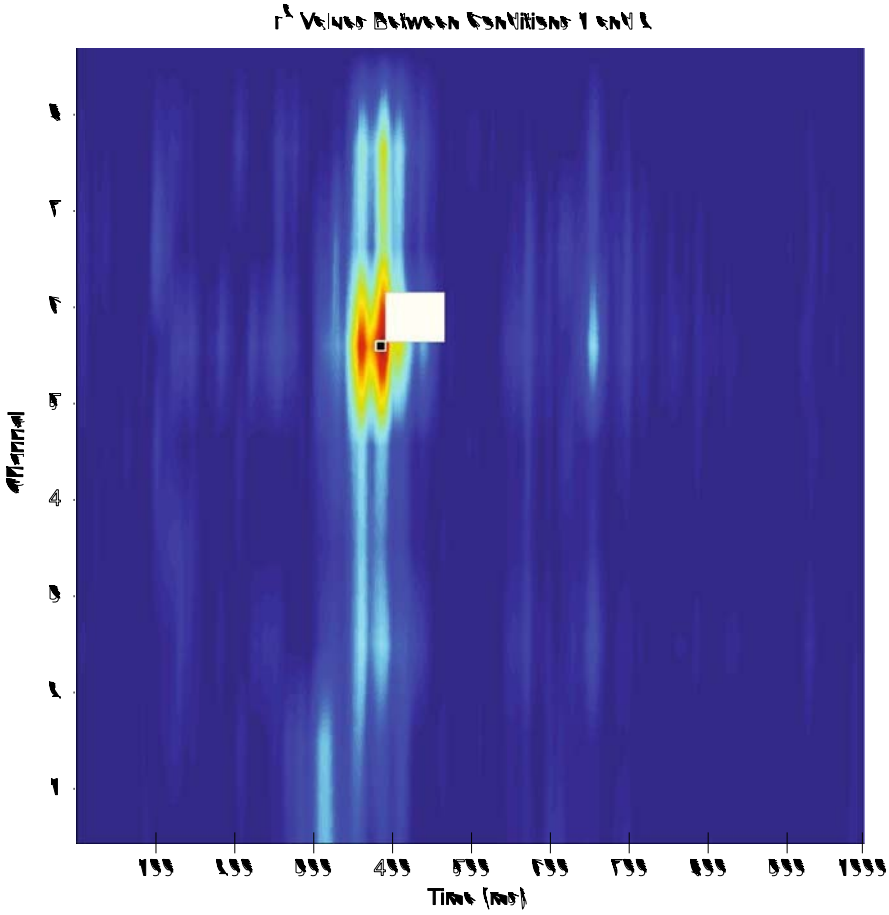


Fig. 5.7 Feature map produced by the “Offline Analysis” tool

Selecting Features (continued)

6. Additionally before moving on, determine the location of the response seen.
   The P300 response is generally observed centered on the Cz electrode, or just
   behind and directly in between the ears, and does not involve the frontal regions of the brain. Assuming these characteristics are present, it is proper to proceed.
7. If there are less than four points that seem appropriate, either because they are
   at the wrong electrodes, at the wrong times, or simply have too low of an r^2
   value, that is fine; three or two values can work, though fewer values used will
   typically result in a lower accuracy.
8. Additionally, it may be helpful to re-run the analysis by setting the Spatial Filter to None, particularly when few channels are used.

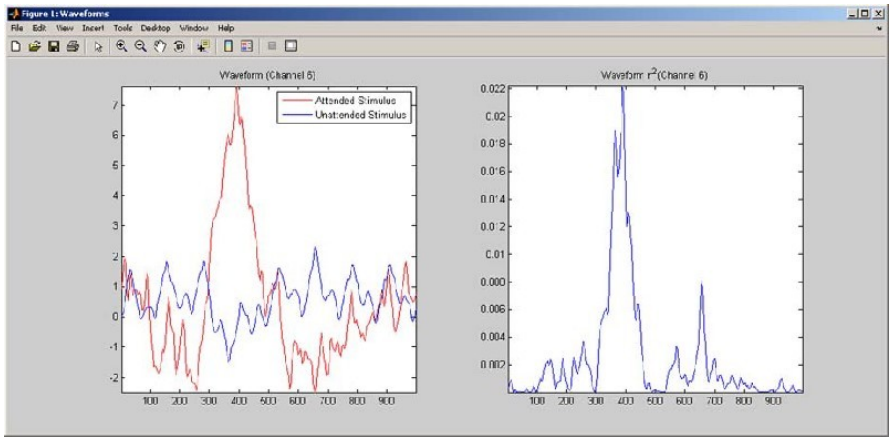


Fig. 5.8 Waveform plot produced by the “Offline Analysis” tool

Similar to what you did in the Mu Rhythm Tutorial, please note the location and time of the best features. Keep in mind that the P300 response generally peaks around the Cz/Pz electrodes, rather than in frontal or lateral regions of the brain.

The next step is to configure BCI2000 to use the selected locations/times.

Storing Subject-Specific Parameters

1. Start BCI2000 using `batch/P3Speller_<amplifier>.bat` file.
2. Click Config, and load the configuration file saved previously.
3. Under the Storage tab, set the SubjectSession parameter to `002`, and the SubjectName parameter to the subject’s initials.
4. Under the Filtering tab, click the Edit Matrix button next to Classifier near the bottom.
5. Change this matrix to have four columns and as many rows as values you are using obtained from the offline analysis, and click Set New Matrix Size.
6. In the first column, labeled Input Channel, enter the channel of the first value you use.
7. In the second column, labeled Input Element (bin), enter the time of the best classification, immediately followed with `ms`,asin`388.7ms`.
8. In the third column, enter `1` as the output channel.
9. In the fourth column, enter `1` if the red line was larger than the blue line in the waveform plot (i.e., Fig. 5.8), and `-1` if the blue line was larger than the red line.
10. Repeat these steps for the remaining values, and close the matrix.
11. If a `Common Average Reference` spatial filter was used in the analysis, under the Filtering tab change the SpatialFilterType parameter to `Common Average Reference`; otherwise, leave it as `None`.
12. Click Save Parameters to save this file, naming it however you deem fit.

Storing Subject-Specific Parameters (continued)

13. Use this new parameter file to repeat the calibration session a few times. The goal of these repeated sessions is to increase the accuracy of the speller experiment.
14. When accuracy is at an acceptably high level (>90%), click Config, go to the Application tab, and delete the contents of the Text to Spell field, set InterpretMode to `online free mode`, and make sure the DisplayResults box is checked.
15. Click on Edit Matrix next to TargetDefinitions and scroll to the bottom. In the first column, replace 9 with BS (for “backspace”). In the second column replace 9 with <BS>.
16. Click Save Parameters, and change the `copy_spell` portion of this parameter file name to `free_spell`.
17. This parameter file is now ready to use for that specific subject for future P300 spelling experiments.

5.3.3.2 P300 Classifier

The use of the Offline Analysis program will familiarize the reader with the characteristics of the P300 response. At the same time, manually selecting the best features will typically result in reduced performance compared to when the features are automatically selected. Such automatic selection is performed using the P300 Classifier tool that is provided with BCI2000. This stand-alone program determines optimal features (i.e., signal times and channels) and corresponding weights automatically, and outputs those in a classifier matrix. Use of this program streamlines the configuration process at the expense of decreased hands-on experience with BCI data and the BCI2000 program itself.

For detailed instructions on using the P300 Classifier, see Chap. 10.11. To generate a parameter file containing optimized classification settings:

Using the P300 Classifier

1. Navigate to `BCI2000/tools/P300Classifier`, and double-click `P300Classifier.exe`.
2. The P300 Classifier program appears.
3. In the top of the window, click on Load Training Data Files.
4. Select the data files collected from the four calibration runs, located at `BCI2000/data/P300/<Subject Initials>001/`.
5. To show the default settings, press the Parameters button. However, none of

these settings should be changed right now.

6. Go back the Data pane, and click on Generate Feature Weights. To observe the progress, press the Details button.
7. On the Details pane, take note of how many sequences are required for 100%
accuracy. This will be used later to configure the P300 spelling session.

Using the P300 Classifier (continued)

8. If less than 100% accuracy is achieved, your subject may not produce a strong P300 response, or you may need to collect more calibration data prior to proceeding.
9. When the classification is complete, click on Write *.prm File on the Data pane. Create a name for the parameter file, which will be used during the P300 spelling session later.

5.3.4 Performing a P300 Spelling Session

Now that the appropriate classification parameters have been determined, it is possible to perform a real spelling session. First, you should provide the subject with instructions that explain what they should expect, for example:

Subject Instructions

1. You will see a matrix of characters, numbers, and punctuation marks.
2. To choose a certain letter, concentrate on it by counting each time it flashes.
3. After some time, the computer determines from your brain signals which character you want and appends it to the text field located at the top of the window.
4. If the letter that appeared is not what you intended, concentrate on the "backspace" or "undo" field to remove it.
5. As in the previous sessions, please refrain from blinking, looking around other than at the letter you want to select, moving your head or body, speaking, or swallowing. These actions produce artifacts in the data that can throw off your selection.

The subject should be further assisted by providing a comfortable chair and a dimly lit room. The experimenter must carefully monitor the EEG and alert the subject in case he/she has forgotten some of the instructions. When the experimenter is sure that the instructions have been well understood, the recording session may start.

Starting a P300 Session

1. Open BCI2000 with `batch/P3Speller_<amplifier>.bat`.
2. Click on Config, then Load Parameters.

3. Load the base parameter file for your amplifier, and then the parameter file
   saved previously using either the `OfflineAnalysis` tool or the `P300 Classifier` tool.
4. If the P300 Classifier was used, in the Filtering tab, set EpochsToAverage to the ideal number found by how many flashes were needed to attain maximum accuracy. If the Offline Analysis tool was used, set this to 15.

Starting a P300 Session (continued)

5. In the Application tab, set NumberOfSequences to this number as well.
6. Delete the contents of the Text to Spell field.
7. Set InterpretMode to `online free mode`.
8. Make sure the DisplayResults box is checked.
9. Click on Edit Matrix next to TargetDefinitions, and scroll to the bottom.
10. In the first column, replace 9 with BS.
11. In the second column, replace 9 with <BS>.
12. Click Save Parameters and name as you see fit. Typically this parameter file would include the name of your amplifier with `P300` and the subject's initials, along with `Free_Spell`. This file is now the file used for that specific subject in later P300 spelling sessions.
13. Click Set Config to view the EEG signal, and prepare the subject for EEG recording.
14. Note: When your latency value does not refer to an exact sample position, a warning message will be displayed once you click SetConfig. You may safely ignore that warning message for now.
15. On the subject's screen, a speller matrix the subject is already familiar with from the initial session is presented. However, in this session, no text is suggested; rather, the subject may choose freely which letters, words, and sentences to write.
16. Click the Start button to start the spelling experiment.

5.3.4.1 Multiple Sessions

Once a run has ended, BCI2000 goes into suspended state. Further runs will be added to the session when you click Resume. When starting the next session (typically, on a different day), don't forget to increment the SessionNumber parameter on the Storage tab. Otherwise, new runs will be added to the previous session's directory. BCI2000 will never overwrite existing data files but increment the largest run number that exists in a session directory. Moreover, it documents date and time in the StorageTime parameter. This allows the experimenter to later associate data files with multiple sessions by their time and date, even if the SessionNumber parameter has not been increased.

References

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Chapter 6
Advanced Usage

The previous chapters provided an overview of the BCI2000 environment, and provided tutorials for commonly-used functionality. BCI2000 also provides a variety of advanced techniques for controlling and analyzing experiments. These will be covered in this chapter.

6.1 Matlab MEX Interface

6.1.1 Introduction

The BCI2000 distribution includes Matlab MEX files for manipulating BCI2000 data files, and for other tasks. MEX files allow the execution of externally compiled code from within Matlab. Because Matlab code is interpreted at runtime, and MEX files contain binary code that has been compiled prior to use, MEX files are generally faster than equivalent Matlab code. BCI2000 MEX allow for convenient access to BCI2000 data files or functions directly from Matlab.

6.1.2 Using BCI2000 MEX Files

6.1.2.1 Microsoft Windows 32

The BCI2000 binary distribution comes with pre-compiled MEX files for 32-bit Microsoft Windows platforms. Add `BCI2000/tools/mex` to your Matlab path to use these files, or copy them to the directory that holds your Matlab analysis scripts.

6.1.2.2 Other Platforms

BCI2000 comes with pre-built MEX files for a number of other platforms that include 64-bit Windows, Mac OS X, and Linux 32-bit as well as 64-bit. Support for

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these MEX files is experimental, and they may or may not work on your particular
configuration.

6.1.3 Building BCI2000 MEX Files

Typically, you will use pre-built binary versions of BCI2000 MEX files. If you need to build BCI2000 MEX files yourself, please follow the instructions below.

6.1.3.1 Microsoft Windows

Compiling MEX files under Windows requires the Borland C++ compiler (a free command line version is available at
http://www.codegear.com/downloads/free/cppbuilder). To build MEX files,

- open a console window,
- change to the `BCI2000/src/Tools/mex` directory,
- execute `make` from there.
  For Matlab versions up to 7.5 (Release 2007b), alternatively the buildmex script

may be used after configuring the `mex` command to use the Borland compiler. For
newer versions of Matlab, the `mex` command does not support the Borland compiler any more; still, using the `make` command as described above should work with
newer versions of Matlab as well.

6.1.3.2 Other Platforms

For platforms other than 32-bit Windows, BCI2000 provides a Matlab script that
can be used to build MEX files.

- Independently of system libraries, Matlab creates its own execution environment
  for MEX files. For MEX files, this means that they usually won't work unless compiled with a version of the gcc compiler that matches the one used to build
  Matlab itself, and linked against libraries that match the ones used by Matlab. To
  check, see Matlab's list of compatible compiler versions.
- After downloading the BCI2000 source code, start Matlab and make sure that the mex command is configured to use the gcc compiler. Typing `help mex` from the Matlab command line will guide you in configuring the mex command.

- Change Matlab's working directory to `BCI2000/src/core/Tools/mex/`.
- Execute `buildmex` from the Matlab command line.
- Add `BCI2000/tools/mex` to your Matlab path to use the newly built MEX files.

6.1.4 BCI2000 MEX Functions

6.1.4.1 load_bcidat

```
[ signal, states, parameters ] ...
    = load_bcidat( 'filename1', 'filename2', ... );
```

This function loads signal, state, and parameter data from the files whose names
are given as function arguments.

Example Examples for loading multiple files:

```
files = dir( '*.dat' );
[ signal, states, parameters ] = ...
    load_bcidat( files.name );

files = ...
    struct( 'name', uigetfile( 'MultiSelect', 'on' ) );
[ signal, states, parameters ] = ...
    load_bcidat( files.name );
```

For multiple files, the number of channels, states, and signal type must be con-
sistent across all files. By default, signal data will be in raw A/D units, and will be represented by the smallest Matlab data type that accommodates them. To ob-
tain signal data calibrated into physical units (µV), specify `'-calibrated'` as an option anywhere in the argument list. (All online signal processing in BCI2000 is
performed on calibrated signals.) The states output variable is a Matlab struct with
BCI2000 state names as member names. Because there is one state value for each
signal sample, the number of state values equals the first dimension of the signal
output variable. The parameters output variable is a Matlab struct with BCI2000
parameter names as member names. Individual parameter values are represented as
cell arrays of strings in a Value struct member, and additionally as numeric matrices
in a NumericValue struct member. When there is no numeric interpretation, the cor-
responding matrix entry will be NaN. For nested matrices, no NumericValue field is provided. If multiple files are given, parameter values will be those contained in
the first file.

This MEX file has the option to load only a range of samples in individual files. The following command will load a subset of samples defined by first and last sample index:

```
[ signal, states, parameters ] ...
    = load_bcidat( 'filename', [first last] );
```

Specifying `[0 0]` for an empty sample range makes it possible to read states and parameters from a file without reading sample data:

```
[ signal, states, parameters ] ...
    = load_bcidat( 'filename', [0 0] );
```

6.1.4.2 save_bcidat

```
save_bcidat( 'filename', signal, states, parameters );
```

This MEX function saves signal, state, and parameter data into the named BCI2000 file. The signal, state, and parameter arguments must be Matlab structs as created by the `load_bcidat`, or `convert_bciprm` MEX files. Signal data is always interpreted as raw data, i.e., it will be written into the output file unchanged.

The output file format is deduced from the output file's extension, which may be `.dat`, `.edf`, or `.gdf`. When no extension is recognized, the BCI2000 dat file format is used.

6.1.4.3 convert_bciprm

This MEX function converts BCI2000 parameters from Matlab struct into string representation and back.

```
parameter_lines = convert_bciprm( parameter_struct );
```

Converts a BCI2000 parameter struct (as created by `load_bcidat`) into a cell array of strings that contain valid BCI2000 parameter definition strings. When the input is a cell array rather than a Matlab struct, `convert_bciprm` converts the definition strings into a valid BCI2000 parameter struct (ignoring the NumericValue field if present).

```
parameter_struct = convert_bciprm( parameter_lines );
```

6.1.4.4 mem

This MEX function estimates the power spectrum using the autoregressive (AR-based) spectral estimator that is also used online in the ARFilter. The calling syntax

is:

```
[spectrum, frequencies] = mem(signal, parms);
```

The variables signal and spectrum have dimensions channels × values; the variable parms is a vector of parameter values:

- model order,
- first bin center,
- last bin center,
- bin width,
- evaluations per bin,
- detrend option (optional, 0: none, 1: mean, 2: linear; defaults to none),
- sampling frequency (optional, defaults to 1).

6.2 Operator Scripting

Operator scripts automate actions that otherwise would be performed by the user, e.g., starting or suspending system operation. Scripts may be contained in script files, or given immediately in the operator module's preferences dialog. There is also an option to specify scripts from the command line when starting the operator module. These possibilities are described in more detail below.

6.2.1 Events

Execution of particular scripts can be triggered by different events that occur during various stages of BCI2000 system operation:

- OnConnect: This event is triggered at startup, i.e., as soon as all modules are connected to the operator module.
- OnSetConfig: This event is triggered each time a set of parameters is applied to the system. This happens when the user clicks the SetConfig button. Execution of the SETCONFIG scripting command also triggers this event.
- OnStart, OnResume: These events correspond to the Start/Resume button. One of these events is also triggered when the Running state variable is set to 1 from a script. Whether OnStart or OnResume is triggered depends on whether the system has been running before with the current set of parameters.
- OnSuspend: This event is triggered when the system goes from running into suspended mode. This happens whenever the Running state variable changes from 1

to 0. This may happen when the user clicks Suspend, when the application module switches the system into suspended mode, or when a script sets the Running
state variable to 0.

- OnExit: This event is triggered when the operator module quits. Execution of the QUIT scripting command also triggers this event.

6.2.2 Scripting Commands

BCI2000 scripts consist of sequences of the scripting commands that are terminated with either a DOS line ending sequence or a semicolon (;). When the semicolon is used to terminate commands, a line may contain multiple commands. Scripts are case-sensitive, and commands must be spelled uppercase as shown in the list below.

In the Operator module's preferences dialog, scripts may be entered for each of the events listed above. Scripts may be specified as paths to script files, or as immediate one-line scripts. Entries that start with a minus sign (-) are treated as one-line scripts, which may contain multiple commands separated with semicolons.

Scripts may also be specified from the command line used to start up the operator module. There, event names are followed with the content of the respective preference entry, enclosed in double quotes ("..."). The list of currently supported scripting commands is given below:

- `LOAD PARAMETERFILE <file>`
  Loads a parameter file specified by its path and name. Relative paths are interpreted relative to the operator module's working directory at startup. Usually, this matches the executable's location in the `prog` directory. The parameter file name must not contain white space. Thus, please use HTML-type encoding for white space characters, such as `Documents%20and%20Settings` when referring to the `Documents and Settings` folder.
- `SETCONFIG`
  Applies current parameters to the system. Corresponds to the SetConfig button.
- `INSERT STATE <name> <bit width> <initial value>`
  Adds a state variable to the system. State variables are defined by name, bit width, and initial value. This command may not be used after system initialization has completed, i.e., its use is restricted to the OnConnect event.
- `SET STATE <name> <value>`
  Sets the named state variable to the specified integer value. Setting the `Running` state to `1` will start system operation; setting it to `0` will suspend the system.
- `QUIT`
  Quits the operator module after terminating all BCI2000 modules.
- `SYSTEM <command line>`
  Executes a single-line shell command.

6.2.3 Examples

Example 1 To add a state variable called Artifact, and to set it using the operator's function buttons, do this:

1. Enter the following line under After All Modules Connected in the operator's preferences dialog (note the minus sign):

```
-INSERT STATE Artifact 1 0
```

2. Under Function Buttons, enter `Set Artifact` as the name of button 1, and as its command, enter (note there is no minus sign): `SET STATE Artifact 1`
3. Enter `Clear Artifact` as the name of button 2, and as its command enter `SET STATE Artifact 0`

Example 2 The following example shows how to specify script commands from the command line. It fully automates BCI2000 operation by loading a parameter file, applying parameters, starting the system once the parameters are applied, and quitting the system once the run is over. For better readability, the example is broken across lines; for execution, the command needs to be entered as a single line.

```
operat.exe
        --OnConnect  "-LOAD PARAMETERFILE
                      ..\parms\examples\CursorTask\
                      SignalGenerator.prm; SETCONFIG"
        --OnSetConfig "-SET STATE Running 1"
        --OnSuspend  "-QUIT"
```

6.3 Command Line Options

6.3.1 Operator Options

The operator module makes it possible to specify scripts from the command line. Command line options correspond to script entries in the operator's preferences dialog. The following options exist: `--OnConnect`, `--OnExit`, `--OnSetConfig`, `--OnSuspend`, `--OnResume`, and `--OnStart`.

After each option, a white space is expected, followed with a double-quote enclosed string. Examples are:

- `--OnConnect "C:\scripts\onconnect.bciscript"`
- `--OnConnect "-LOAD PARAMETERFILE ..\parms\myparms.prm"`

6.3.2 Core Module Options

Using command line options at the startup of BCI2000 modules, it is possible to

run different BCI2000 modules on different machines on a network, change the
data format for brain signal recordings, switch on debugging messages, or automate BCI2000 operation.

Core Modules, i.e., the Data Acquisition, Signal Processing, and Application Module, share the same command line syntax:

```
<ModuleName> <operator IP>:<operator port>
--<option1>-<value1>
--<option2>-<value2> ...
```

All arguments are optional.

At startup, each core module connects to the operator module. If no IP address is specified on the command line, the connection is opened to the local machine using 127.0.0.1 as an IP address. When no port is given, each module uses a specified default port. Normally, there is no need to change port numbers.

Any number of options may be given, starting with a double minus sign. As indicated above, option names and values are combined with a single minus sign, to form a continuous character string. Each option is translated into a BCI2000 parameter using its name as a parameter name, and its value as a parameter value. When a parameter with the given name already exists, its value will be changed from the default to match the value given on the command line. When no parameter with that name exists, it is added to the System parameter section. Parameter values must not contain white spaces on the command line; however, white space may be encoded in HTTP fashion, e.g., using '%20' as a replacement for a single space character.

In addition, there are a few miscellaneous options:

- Specifying `--version` will display version information, and then quit.
- The FileFormat option will switch between different file formats used for data recording. The output file format is determined at module startup, and cannot be changed by modifying the FileFormat parameter from the operator module's parameter dialog.
- The Debug option will make a module send Debug Messages that appear in the operator module's log window.
- The LogKeyboard, LogMouse, and LogJoystick options will enable recording of key presses, mouse, and joystick movements, respectively.

6.3.3 Data File Formats

This section describes which data formats are available for output and how to select
one of them.

At runtime, selection of a file format is achieved by specifying a command line
parameter to the source module, as in

```
gUSBampSource --FileFormat=Null
```

or

```
SignalGenerator --FileFormat=GDF
```

Typically, source modules are launched from batch files contained in the "batch" directory, and their command line parameters are specified there. Internally, support for various output formats is provided by File Writer classes (pieces of software) implementing the interface defined by the `GenericFileWriter` class. Thus, a programmer can add support for a new output format by deriving a new class from `GenericFileWriter`, and adding it to existing source modules.

On the command line, the value that follows the last minus character, appended with `FileWriter`, will be matched against the names of all `GenericFileWriter` descendants present in the source module. In the first example, the `NullFileWriter` class will be used for data output (which will not produce any output file), and the `GDFFileWriter` class will be used in the second example.

BCI2000 File Format (`--FileFormat=BCI2000`) Parameters, BCI2000 state variables, and brain signal data will be written into a BCI2000 data file in the BCI2000 data format. This is also the default if no file format is specified explicitly.

Null File Format (`--FileFormat=Null`) No information is recorded. Individual filters may still write log files to the directory defined by the DataDirectory, SubjectName, and SubjectSession parameters.

EDF File Format (`--FileFormat=EDF`) EDF (European Data Format) ([1], http://www.edfplus.info/specs/edf.html) is a standard for biosignal data that is particularly popular in the area of sleep research. EDF is limited to 16-bit data. BCI2000 state variables will be mapped to additional signal channels. BCI2000 parameters cannot be represented in EDF format. Setting the SaveAdditionalParameterFile parameter to 1 will save a separate BCI2000 parameter file along with the EDF data file.

GDF File Format `--FileFormat=GDF` GDF is a recently designed general data format for biosignals ([3], http://biosig.sf.net). Building on EDF, GDF allows for arbitrary numeric data types, introduces an event table, and provides standardized encoding of events. At present, BCI2000 supports Version 2.10 of the GDF format specification. BCI2000 does not prescribe the meaning of its state variables. GDF, on the other hand, associates a fixed set of events with certain numeric codes. Thus, a general mapping of BCI2000 states onto GDF events is

not possible. Instead, GDF events are created via a user-defined set of mapping
rules in the EventCode parameter, which also has a set of rules predefined for the
most important cases. Besides GDF events, BCI2000 state variables will also be
mapped to additional signal channels the same way as for EDF. Since version 2.0,
GDF provides additional header space for metadata which is organized as a se-
quence of tag/length/value structures. BCI2000 uses such a structure – tagged with
a “BCI2000” tag – to store parameters. Within the GDF data field, the same hu-
man readable format is used that applies to BCI2000 parameter files and .dat file
headers.

6.4 AppConnector

6.4.1 Introduction

The BCI2000 external application (i.e., AppConnector) interface provides a bi-directional link to exchange information with external processes running on the same machine, or on a different machine over a local network. Via the external application interface, read/write access to BCI2000 state vector information and to the control signal is possible. To list examples of possible uses, external applications may read the ResultCode state to access the classification result, set the TargetCode state to control the user's task, or get access to the control signal that is calculated by SignalProcessing so as to control an external output device (such as a robotic arm or a web browser). Multiple instances of BCI2000 running on separate machines may share sequencing and control signal information, allowing for interactive applications such as games.

6.4.2 Scope

The scope of this interface is to provide access to internal BCI2000 information for cases in which the generation of a full-fledged BCI2000 module is impractical. Such a case might be the control of external applications that practically do not allow full incorporation into the BCI2000 framework (such as the Dasher system [2] for efficient low-bandwidth spelling).

This interface is not intended to replace the existing BCI2000 framework for BCI2000 communication. The advantages of writing modules that are fully integrated into the BCI2000 framework are that their configuration is achieved through the same interface as other BCI2000 configurations, that this configuration is stored in the data file along with all other system parameters, and that the state of the mod-

ule at any given time is encoded in event markers that are also stored in the data
file.

In contrast, control of an external device using the AppConnector interface implies that the configuration of the external device has to be done outside of BCI2000, that this corresponding configuration is not stored along with the data file, and that the internal state of the output device is not automatically saved together with the brain signals (although it is possible to introduce your own state variables for this purpose using the operator module's INSERT STATE scripting command). Having no configuration and state information present in the data file will make it more difficult to reconstruct what exactly was going on during an experimental session. It is thus important to keep this in mind when using this possibility.

6.4.3 Design

The design of the external application interface aims at simplicity, and at minimal interference with the timing of the signal flow through the BCI2000 system. With this in mind, we chose a connection-less, UDP-based transmission protocol rather than one based on TCP. This comes at the cost of a possible loss, or reordering of protocol messages. To keep the probability for such losses as low as possible, and their consequences as local as possible, messages have been designed to be short, self-contained, and redundantly encoded in a human readable fashion.

The connectionless nature of UDP implies that there is no server or client in the asymmetric sense that applies for TCP connections. Rather, processes write to local or remote UDP ports, and read from local UDP ports, whenever applicable.
Thus, for bi-directional communication between machine A running BCI2000 and machine B running the external application, there will be two UDP ports involved:

- a port on machine B to which BCI2000 sends its messages for use in the external application, and
- a port on machine A to which the external application sends its messages for use in BCI2000.

In most cases, both BCI2000 and the external application will run on the same machine, i.e., A and B will refer to the same machine, and both ports will be local. Still, they are distinct ports.

For communication that involves a large number of network nodes, or unreliable connections, we suggest using local UDP communication, in conjunction with locally executed TCP/IP server processes that forward messages to a TCP connection between the two remote machines.

6.4.4 Description

For each block of data processed by the BCI2000 system, two types of information

are sent out and may be received from the external application interface:

- the BCI2000 internal state as defined by the values of all BCI2000 states, and
- the BCI2000 control signal.

Sending data occurs immediately after the task filter of the application module processes the data; receiving occurs immediately before the task filter. This ensures that changes resulting from user choices are sent out immediately, and that received information will immediately be available to the task filter. IP addresses and ports are user-configurable. Sending and receiving may not use the same address and port.

6.4.5 Protocol

Each message in the protocol consists of a name and a value that are separated by a white space, and that are terminated with a single newline ('\n'==0x0a) character.
Names may identify

- BCI2000 states by name – then followed by an integer value in decimal ASCII representation;
- Signal elements in the form Signal(<channel>,<element>) – then followed by a float value in decimal ASCII representation. Channel and element indices are given in zero-based form.

6.4.6 Examples

```
Running 0\n
ResultCode 2\n
Signal(1,0) 1e-8\n
```

The lines above show examples for valid AppConnector transmissions. If the first line was sent to BCI2000, it would switch BCI2000 into the suspended state.
It is important to note that AppConnector communication is not possible during the suspended state.

The meaning of control signals depends on the used application module. For the BCI2000 cursor task, there are up to three control signal channels (channel indices 0, 1, and 2), each of which consists of one value (i.e., element). These three channels correspond to cursor velocity in X, Y, and Z direction, respectively. For example,

```
Signal(1,0) 1e-2\n
```

would indicate a value of 1e–2 for vertical cursor velocity.

6.4.7 Parameterization from Within BCI2000

BCI2000 reads AppConnector protocol lines from a local IP socket specified by the ConnectorInputAddress parameter, and writes such lines to the socket specified by the ConnectorOutputAddress parameter. Sockets are specified by an address/port combination. Addresses may be host names, or numerical IP addresses. Address and port are separated by a colon, such as in `localhost:5000` or `134.2.103.151:20321`.

Incoming protocol lines are filtered by name using a list of allowed names, which

are defined in the ConnectorInputFilter parameter. To allow signal messages, al-
lowed signal elements must be specified including their indices. To allow all names, enter an asterisk (*) as the only list entry.

6.4.8 Examples

6.4.8.1 BCI2000 Example Code

You can find simple AppConnector examples in the `BCI2000/src/contrib/AppConnectorApplications/` directory. For example, in `ParallelSwitch` there is a simple program that uses AppConnector information from BCI2000 to control the state of the parallel port. As another example, in `AppConnectorExample` you will find a GUI application that interacts with BCI2000 states.

The following listing shows a simple C++ example that reads BCI2000 AppConnector messages using the BCI2000 sockstream class:

```
#include <iostream>
#include "SockStream.h"

using namespace std;

int main( int argc, char** argv )
{
  const char* address = "localhost:5000";
  if( argc > 1 )
    address = argv[ 1 ];

  receiving_udpsocket socket( address );
  sockstream connection( socket );
  string line;
  // Print each line of BCI2000 input to stdout.
  while( getline( connection, line ) )
    cout << line << endl;

  return 0;
}
```

Note: This example program uses the BCI2000 socket stream utility classes contained in `src/shared/utils/SockStream.cpp`. You will need to add this file to your project to build the example program.

6.4.8.2 An External Application Reading Information from BCI2000, Running Locally

- Set the ConnectorOutputAddress parameter to a local address above 1,024, such as `localhost:5000`.
- In the external application, create a UDP socket and bind it to BCI2000's output port, i.e., `localhost:5000`.
- Read from that socket as you would from a TCP socket.

6.4.8.3 An External Application Reading Information from BCI2000, Running on a Remote Machine

- Set the ConnectorOutputAddress parameter to a remote address with a port above 1,024, such as `134.2.102.151:20321`.
- In the external program, create a UDP socket, and bind it to the remote machine's external address, i.e., `134.2.102.151:20321` rather than `localhost:20321`.
- Read from that socket as you would from a TCP socket.

6.4.8.4 An External Application Sending Information to BCI2000, Running Locally

- Set the ConnectorInputAddress parameter to a local address with a port above 1,024, such as `localhost:5001`.
- Set the ConnectorInputFilter to `*` (a single asterisk).
- In the external application, create a UDP socket and bind it to BCI2000's input port, i.e., `localhost:5001`.
- Write valid AppConnector lines to that socket at any time.

6.4.8.5 An External Application Sending Information to BCI2000, Running on a Remote Machine

- Set the ConnectorInputAddress parameter to the local machine's external address, and a port above 1,024, such as `bci2000machine.yourdomain.org:20320`.
- In the external program, create a UDP socket and bind it to the BCI2000 machine's external address, i.e., `bci2000machine.yourdomain.org:20320`.
- Write valid AppConnector lines to that socket at any time.

6.5 Expression Filter

BCI2000 provides a powerful mechanism to manipulate and modify data processing in the filter chain without the need for recompilation. This allows signal processing results to be combined with or added to BCI2000 state values. For example, it is possible to replace brain control of a cursor with joystick control simply by entering

the appropriate values into the Expression Filter matrix (this example assumes that
joystick logging is enabled as described in Sect. 6.3.2):

```
JoystickXpos
JoystickYpos
```

The Expression Filter reference in Sect. 10.7.4 contains detailed information on
using the Expression Filter, including several examples.

References

1. Kemp, B., Värri, A., Rosa, A.C., Nielsen, K.D., Gade, J.: A simple format for exchange of digitized polygraphic recordings. Electroencephalogr. Clin. Neurophysiol. 82(5), 391–393 (1992)
2. MacKay, D.: Dasher – An efficient keyboard alternative. Adv. Clin. Neurosci. Rehabil. 3(2), 24 (2003)
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Chapter 7
Programming Reference

7.1 Building BCI2000

This section describes how to build BCI2000 V2.0, i.e., how to create the BCI2000
executables from their source code. This process may be slightly different for
BCI2000 V3.0.

7.1.1 Why Build from Source

Typically, you will install BCI2000 from its binary distribution, and do not need to build BCI2000, unless you:

- want to always use its most current SVN version,
- want to create your own module by modifying an existing one, or create a new
  one from scratch.

7.1.2 Tools Required

Building/compiling BCI2000 requires Borland's C++ Builder 6, or Borland/CodeGear Development Studio 2007/2009. The operator GUI and application modules currently require the Borland VCL library. (BCI2000 V3.0 will also support VisualStudio and MinGW, and will be based on the cross-platform library Qt.) Certain non-GUI related parts of BCI2000 can be built using the freely available
Borland C++ compiler, including the Matlab MEX files.

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7.1.3 How to Build

Command-line builds require a working installation of Borland C++ Builder 6. This section describes how to build BCI2000 from the command line, from the Borland
C++ 6 IDE, and from newer versions of the Borland C++ environment.

Building BCI2000 from the Command Line

1. Open a Windows `cmd` shell, e.g., by choosing `Run...` from the Start Menu and entering `cmd`.
2. Change to the BCI2000 `src` directory by typing `cd c:\BCI2000\src`, if BCI2000 is located at the root level of the C drive.
3. Type `make` from the command prompt.
4. If you updated or edited any of the source files, and experience linker errors or other unexpected behavior, execute `make clean && make all`.
5. For build versioning, execute `make build` rather than `make` or `make all`. This will update the build information visible in the BCI2000 "Version" parameters, and in the "About" boxes of BCI2000 GUI applications.

Building BCI2000 Using the Borland C++ Builder 6 IDE

1. Open the file `BCI2000/src/BCI2000.bpg` with the IDE by double-clicking it.
2. Make sure the "Project Manager" view is visible to the left (choose "Project Manager" from the View menu to display it).
3. Right-click the topmost project (located immediately below the line reading
"BCI2000"), and choose `Make all from here`.
4. To get rid of possible inconsistencies from earlier builds, choose `Build all from here` rather than `Make all from here`.

Compiling BCI2000 with Borland C++ Builder (BCB) 2006/2007/2009

1. When using BCB 2006, please make sure to install all available updates from
http://cc.embarcadero.com/reg/bds. The originally shipped version of BCB 2006 is defective and will not work without updating. We recommend updating to BCB 2007 or BCB 2009.
2. Open the file `BCI2000/src/BCI2000.bpg` from within Borland Developer Studio. This will import all existing projects into BDS project files.
3. In the project manager (at the top right), right-click the topmost project and
choose `Make all from here`.
4. To get rid of possible inconsistencies from earlier builds, choose `Build all from here` rather than `Make all from here`.

Compiling BCI2000 with Borland C++ Builder (BCB) 2006/2007/2009 (continued)

5. Command-line builds cannot be done with Borland C++ Builder 2007/2009 because it lacks a project-to-makefile conversion utility. Still, the Matlab MEX files may be compiled from the command line as described in Sect. 6.1.
6. When using BCB 2006, you may experience invalid property runtime errors when running BCI2000. This may be due to imperfect import of *.dfm files. Make sure to install all available updates, then import a clean version of the
BCI2000 source tree. If this doesn't help, consider updating to a newer version of the Developer Studio.

7.1.3.1 Building Contributions

From the Command Line After building BCI2000 from the command line, the `makefiles` file in the `BCI2000/src` directory contains a full list of subprojects. Those from the contribution section are commented out with a # character in front.
(BCI2000 consists of core components that were implemented by the BCI2000
development team, and contributed components that were designed by external
contributors.) When you remove the # character, and do a `make all` or `make build`, the additional project will be included into the build. Likewise, you may speed up builds by commenting out parts of the core distribution that you don't
need.

From the IDE Open the contrib project group in the `src/contrib` directory, and build the contributions you want.

7.1.4 Starting up BCI2000

After compilation, a desired configuration of BCI2000 may be started by execut-
ing an appropriate batch file from the top level `BCI2000/batch` directory. Once a particular configuration of BCI2000 is started, simply load a parameter file with the
same name as the batch file from the `BCI2000/parms/examples` directory. If you need a configuration for which no batch file exists, just modify a copy of a batch file
that is close to your needs.

7.2 Writing a Custom Source Module

In this section, we walk you through the steps to write a new source module for a
fictional data board. The concepts presented here will likely be similar for any data
acquisition board that provides a C/C++ interface.

Data acquisition modules consist of code that provides generic BCI2000 framework functions (such as data storage), and code that implements access to specific data acquisition hardware. When implementing a source module, you only need to be concerned with the latter. Specifically, you need to implement a function that waits for and reads A/D data, and several helper functions that perform initialization and cleanup tasks. Together, these functions form a class derived from `GenericADC`.

7.2.1 Example Scenario

Your Tachyon Corporation A/D card comes with a C-style software interface declared in a header file `TachyonLib.h` that consists of three functions:

```
#define TACHYON_NO_ERROR 0
int TachyonStart( int inSamplingRate,
                  int inNumberOfChannels );
int TachyonStop( void );
int TachyonWaitForData( short** outBuffer,
                        int inCount );
```

From the library help file, you learn that `TachyonStart` configures the card and starts acquisition to some internal buffer; that `TachyonStop` stops acquisition to the buffer, and that `TachyonWaitForData` will block execution until the specified amount of data has been acquired, and that it will return a pointer to a buffer containing the data in its first argument.

Each of the functions will return zero if everything went well, otherwise some error value will be returned. Luckily, Tachyon Corporation gives you just what you need for a BCI2000 source module, so implementing the ADC class is quite straightforward.

As a remark, the .lib file provided with your device may be in a format that is not suitable for the Borland compiler. In this case, use the `implib` tool that comes with Borland to create a Borland-compatible import library (.lib file) for your device's .dll file.

7.2.2 Writing the ADC Header File

In your class' header file, `TachyonADC.h`, you write:

```
#ifndef TACHYON_ADC_H
#define TACHYON_ADC_H
```

```
#include "GenericADC.h"

class TachyonADC : public GenericADC
```

```
  (continued)
  {
   public:
     TachyonADC();
     ~TachyonADC();

     void Preflight( const SignalProperties&,
                     SignalProperties& ) const;
     void Initialize( const SignalProperties&,
                      const SignalProperties& );
     void Process( const GenericSignal&,
                   GenericSignal& );
     void Halt();

   private:
     int  mSourceCh,
          mSampleBlockSize,
          mSamplingRate;
  };
  #endif // TACHYON_ADC_H
```

7.2.3 ADC Implementation

In the .cpp file, you will need some #includes, and a filter registration:

```
  #include "TachyonADC.h"
  #include "Tachyon/TachyonLib.h"
  #include "BCIError.h"

  using namespace std;

  RegisterFilter( TachyonADC, 1 );
```

From the constructor, you request parameters and states that your ADC needs;
from the destructor, you call `Halt` to make sure that your board stops acquiring
data whenever your class instance gets destructed:

```


  TachyonADC::TachyonADC()
  : mSourceCh( 0 ),
    mSampleBlockSize( 0 ),
    mSamplingRate( 0 )
```

```
(continued)
{
  BEGIN_PARAMETER_DEFINITIONS
    "Source int SourceCh=        64 64 1 128 "
        "// number of digitized channels",
    "Source int SampleBlockSize= 16 5 1 128 "
        "// number of samples transmitted at a time",
    "Source int SamplingRate=    128 128 1 4000 "
        "// the sample rate",
  END_PARAMETER_DEFINITIONS
}

TachyonADC::~TachyonADC()
{
  Halt();
}
```

7.2.4 ADC Initialization

Your `Preflight` function will check whether the board works with the parameters requested, and communicate the dimensions of its output signal:

```
void TachyonADC::Preflight(
                   const SignalProperties&,
                   SignalProperties& outputProperties )
                   const
{
  if( TACHYON_NO_ERROR !=
        TachyonStart( Parameter( "SamplingRate" ),
                      Parameter( "SourceCh" )
                    )
    )
    bcierr << "SamplingRate and/or SourceCh parameters"
           << " are not compatible"
           << " with the A/D card"
           << endl;
  TachyonStop();
  outputProperties = SignalProperties(
                       Parameter( "SourceCh" ),
                       Parameter( "SampleBlockSize" ),
                       SignalType::int16 );
}
```

Here, the last argument of the `SignalProperties` constructor determines not only the type of the signal propagated to the BCI2000 filters but also the format

of the dat file written by the source module. You might want to write SignalType::int32 or SignalType::float32 instead if your data acquisition hardware acquires data in one of those formats.

The actual Initialize function will only be called if Preflight did not report any errors. Thus, you may skip any further checks, and write:

```
void TachyonADC::Initialize(
                    const SignalProperties&,
                    const SignalProperties& )
{
  mSourceCh = Parameter( "SourceCh" );
  mSampleBlockSize = Parameter( "SampleBlockSize" );
  mSamplingRate = Parameter( "SamplingRate" );
  TachyonStart( mSamplingRate, mSourceCh );
}
```

Balancing the TachyonStart call in the Initialize function, your Halt function should stop all asynchronous activity that your ADC code initiates:

```
void TachyonADC::Halt()
{
  TachyonStop();
}
```

7.2.5 Data Acquisition

Note that the Process() function may not return unless the output signal is filled with data, so it is crucial that TachyonWaitForData is a blocking function. (If your card does not provide such a function, and you need to poll for data, don't
forget to call Sleep(0) or Sleep(1) inside your polling loop to avoid tying up the CPU.)

```
void TachyonADC::Process( const GenericSignal&,
                          GenericSignal& outputSignal )
{
  int valuesToRead = mSampleBlockSize * mSourceCh;
  short* buffer;
  if( TACHYON_NO_ERROR == TachyonWaitForData(
                            &buffer,
                            valuesToRead )
    )
```

```
(continued)
  {
    int i = 0;
    for( int ch = 0; ch < mSourceCh; ++ch )
      for( int s = 0; s < mSampleBlockSize; ++s )
        outputSignal( ch, s ) = buffer[ i++ ];
  }
  else
    bcierr << "Error reading data" << endl;
}
```

7.2.6 Adding the SourceFilter

Most measurement equipment comes with hardware filters that allow you to filter
out line noise. For equipment that does not offer such an option, consider adding the `SourceFilter` to your data acquisition module as described in Sect. 10.3.4.

7.2.7 Finished

You are done! Use your `TachyonADC.cpp` to replace the `GenericADC` descendant in an existing source module, add the `TachyonADC.lib` shipped with your card (or the one you created using `implib`) to the project, compile, and link.

7.3 Writing a Custom Signal Processing Module

The tutorial presented in this section describes how to derive a new filter class from `GenericFilter`, how to check preconditions, initialize your filter, and process data. It will also show you how to visualize the output signal of the filter and present it to the user.

7.3.1 A Simple Low-Pass Filter

The goal in this tutorial is to implement a low-pass filter with a time constant T
(given in units of a sample's duration), a sequence $S_{in,t}$ as input and a sequence
$S_{out,t}$ as output (where t is a sample index proportional to time), and obeying:

$-1/T$

−1/T −1/T

7.3.2 The Filter Skeleton

The resulting filter class is to be called `LPFilter`. We create two new files, `LPFilter.h`, and `LPFilter.cpp`, and put a minimal filter declaration into `LPFilter.h`:

```
#ifndef LP_FILTER_H
#define LP_FILTER_H

#include "GenericFilter.h"

class LPFilter : public GenericFilter
{
 public:
   LPFilter();
   ~LPFilter();

   void Preflight( const SignalProperties&,
                   SignalProperties& ) const;
   void Initialize( const SignalProperties&,
                    const SignalProperties& );
   void Process( const GenericSignal&,
                 GenericSignal& );
};
#endif // LP_FILTER_H
```

Into `LPFilter.cpp` we put the lines:

```
#include "PCHIncludes.h"
#pragma hdrstop

#include "LPFilter.h"

#include "MeasurementUnits.h"
#include "BCIError.h"
#include <vector>
#include <cmath>

using namespace std;
```

7.3.3 The `Process` Function

When implementing a filter, a good strategy is to begin with the `Process` function, and to consider the remaining class member functions mere helpers, mainly

determined by the code of Process. First, we convert the filter's algorithm into the Process code, introduce member variables ad hoc, ignore possible error con-
ditions, and disregard efficiency considerations:

```
void LPFilter::Process( const GenericSignal& input,
                        GenericSignal& output )
{
  for( int ch = 0; ch < input.Channels(); ++ch )
  {
    for( int s = 0; s < input.Elements(); ++s )
    {
      mPreviousOutput[ ch ] *= mDecayFactor;
      mPreviousOutput[ ch ] +=
           input( ch, s)*(1.0-mDecayFactor );
      output( ch, s ) = mPreviousOutput[ ch ];
    }
  }
}
```

7.3.4 The Initialize Member Function

As you will notice when comparing Process to the equations above, we introduced member variables that represent these sub-expressions:

$$\text{mPreviousOutput}[\,] = S_{out,t-1}$$

$$-1/T$$

We introduce these members into the class declaration, adding the following lines after the `Process` declaration:

```
  private:
    float               mDecayFactor;
    std::vector<float> mPreviousOutput;
```

The next step is to initialize these member variables by introducing filter parameters as needed. This is done in the `Initialize` member function: we write it down without considering possible error conditions:

```
void LPFilter::Initialize(
      const SignalProperties& inputProperties,
      const SignalProperties& outputProperties )
```

```
(continued)
{
  // This will initialize all elements with 0
  mPreviousOutput.clear();
  mPreviousOutput.resize( inputProperties.Channels(),
                          0 ) ;
  float timeConstant = Parameter( "LPTimeConstant" );
  mDecayFactor = ::exp( -1.0 / timeConstant );
}
```

Now this version is quite inconvenient for a user going to configure our filter, because the time constant is given in units of a sample's duration, resulting in a need to re-configure each time the sampling rate is changed. A better idea is to let the user choose whether to give the time constant in seconds or in sample blocks.

To achieve this, BCI2000 comes with a utility class `MeasurementUnits` that has a member `ReadAsTime()` that returns values in units of sample blocks (i.e., the natural time unit in a BCI2000 system). Writing a number followed by an `s` will allow the user to specify a time value in seconds; writing a number without the `s` will be interpreted as sample blocks. Thus, our user friendly version of `Initialize` reads:

```
void LPFilter::Initialize( const SignalProperties&,
                           const SignalProperties& )
{
  ...
  // Get the time constant in units of a sample
  // block's duration:
  float timeConstant = MeasurementUnits::ReadAsTime(
                         Parameter( "LPTimeConstant" )
                       );
  // Convert it into units of a sample's duration:
  timeConstant *= Parameter( "SampleBlockSize" );

  mDecayFactor = ::exp( -1.0 / timeConstant );
}
```

7.3.5 The `Preflight` Function

Up to now, we have not considered any error conditions that might occur during execution of our filter code. Scanning through the `Process` and `Initialize` code, we identify a number of implicit assumptions:

1. The time constant is not zero; otherwise, a division by zero will occur.
2. The time constant is not negative; otherwise, the output signal is no longer guaranteed to be finite, and a numeric overflow may occur.

3. The output signal is assumed to hold at least as much data as the input signal
contains.

The first two assumptions may be violated if a user enters an illegal value into
the LPTimeConstant parameter. In such a case, we need to make sure that an error is reported and no code is executed that depends on these two assumptions. For
the last assumption, we request an appropriate output signal from the `Preflight`
function. Thus, the `Preflight` code reads:

```
void LPFilter::Preflight(
       const SignalProperties& inputProperties,
       SignalProperties& outputProperties ) const
{
  float LPTimeConstant
    = MeasurementUnits::ReadAsTime(
        Parameter( "LPTimeConstant" )
      );

  LPTimeConstant *= Parameter( "SampleBlockSize" );

  // The PreflightCondition macro will automatically
  // generate an error message if its argument
  // evaluates to false.
  // However, we need to make sure that its
  // argument is user-readable
  // -- this is why we chose a variable name that
  // matches the parameter name.
  PreflightCondition( LPTimeConstant > 0 );

  // Alternatively, we might write:
  if( LPTimeConstant <= 0 )
    bcierr << "The LPTimeConstant parameter must"
           << " be greater 0"
           << endl;

  // Request output signal properties:
  outputProperties = inputProperties;
}
```

7.3.6 Constructor and Destructor

Because we do not explicitly acquire resources, and do not perform asynchronous
operations, there is nothing to be done inside the `LPFilter` destructor. Our con-

structor will contain initializers for the members we declared, and a BCI2000 pa-
rameter definition for LPTimeConstant. Specifying the empty string (%) for both

low and high range tells the framework not to perform an automatic range check on
that parameter.

```
LPFilter::LPFilter()
: mDecayFactor( 0 ),
  mPreviousOutput( 0 )
{
  BEGIN_PARAMETER_DEFINITIONS
    "Filtering float LPTimeConstant= 16s"
      " 16s % % // time constant for the low pass"
          " filter in blocks or seconds",
  END_PARAMETER_DEFINITIONS
}

LPFilter::~LPFilter()
{
}
```

7.3.7 Filter Instantiation

To have our filter instantiated in a signal processing module, we add a line that contains the `Filter` statement to the module's `PipeDefinition.cpp`. This statement expects a string parameter which is used to determine the filter's position in
the filter chain. If we want to use the filter in the AR Signal Processing module, and place it after the `SpatialFilter`, we add:

```
#include "LPFilter.h"
...
Filter( LPFilter, 2.B1 );
```

to the file `SignalProcessing/AR/PipeDefinition.cpp`. Now, if we compile and link the AR Signal Processing module, we get an "unresolved external" linker
error that reminds us to add our `LPFilter.cpp` to that module's project.

7.3.8 Visualizing Filter Output

Once our filter has been added to the filter chain, the BCI2000 framework will automatically create a parameter VisualizeLPFilter that is accessible under Visualize → Processing Stages in the operator module's configuration dialog. This parameter allows the user to view the LPfilter's output signal in a visualization window. In most cases, this visualization approach is sufficient. For the sake of this tutorial, however,

we will disable automatic visualization, and implement our own signal visualization.

To disable automatic visualization, we override the `GenericFilter::AllowsVisualization()` member function to return `false`. In addition, to present the LPFilter's output signal in an operator window, we introduce a member of type `GenericVisualization` into our filter class:

```
#include "GenericVisualization.h"
...
class LPFilter : public GenericFilter
{
  public:
...
    virtual bool AllowsVisualization()
      const { return false; }

  private:
...
    GenericVisualization  mSignalVis;
};
...
```

`GenericVisualization`'s constructor takes a string-valued visualization ID as a parameter; we need to get a unique ID in order to get our data routed to the correct operator window. Given the circumstances, the string "LPFLT" appears unique enough, so we change the `LPFilter` constructor to read:

```
LPFilter::LPFilter()
: mDecayFactor( 0 ),
  mPreviousOutput( 0 ),
  mSignalVis( "LPFLT" )
{
  BEGIN_PARAMETER_DEFINITIONS
    "Filtering float LPTimeConstant= 16s"
      " 16s % % // time constant for the"
        " low pass filter in blocks or seconds",
    "Visualize int VisualizeLowPass= 1"
      " 1 0 1 / /visualize low pass"
        " output signal (0=no, 1=yes)",
  END_PARAMETER_DEFINITIONS
}
```

In `Initialize`, we add

```
  mSignalVis.Send(
    CfgID::WindowTitle, "Low Pass" );
  mSignalVis.Send(
    CfgID::GraphType, CfgID::Polyline );
  mSignalVis.Send(
    CfgID::NumSamples,
    2 * Parameter( "SamplingRate" ) );
```

Finally, to update the display in regular intervals, we add the following at the end of `Process`:

```
  if( Parameter( "VisualizeLowPass" ) == 1 )
    mSignalVis.Send( output );
```

We might also send data to the already existing task log memo window, adding another member:

```
  GenericVisualization  mTaskLogVis;
```

initializing it with:

```
LPFilter::LPFilter()
: ...
  mTaskLogVis( SourceID::TaskLog )
{
 ...
}
```

and, from inside `Process`, writing some text to it as in:

```
  if( output( 0,0)>10 )
  {
    mTaskLogVis << "LPFilter: (0,0) entry of"
                << " output exceeds 10 and is "
                << output( 0, 0 )
                << endl;
  }
```

7.4 Writing a Custom Matlab Filter

7.4.1 Online Algorithm Verification

In the field of BCI signal processing research, novel methods are often proposed and tested on the basis of existing data. While novel methods can clearly improve performance, it is important to keep in mind that timely feedback of brain signal classification is an essential element of a BCI. Thus, any proposed BCI signal processing method should be verified with respect to its viability and usefulness in a true online setting, in which feedback is provided to the subject in real time.

Such novel methods are usually first developed and tested offline. BCI2000 facilitates the transformation of an existing offline analysis method into a functional online system. To do this, it provides a convenient and simple programming interface. Additionally, a signal processing component may be implemented as a set of Matlab scripts. It is still easy to underestimate the effort required to transform an existing offline implementation of a signal processing algorithm into a functional online implementation. While BCI2000 tries to make the transformation as simple as possible, it cannot remove the effort required to deal with chunks of data, which implies the need for

- buffering: rather than having immediate access to a continuous data set, it may be necessary to maintain an additional data buffer;
- maintaining a consistent state between subsequent calls to the processing script (when using the Matlab interface).

7.4.2 An Example Algorithm in Matlab

In this scenario, we use a simple, straightforward BCI signal processing algorithm designed for the mu rhythm paradigm. This serves as an example to illustrate the necessary steps to modify the algorithm such that it may be used to build an online system in BCI2000.

In the example, signal processing consists of IIR bandpass filtering, followed

with envelope computation, and linear classification. A typical Matlab implementa-
tion of that algorithm might consist of about ten lines:

```
function class_result = classify( data, band, classifier );

% Use as
%   class_result = classify( data, band, classifier )
%
% This function takes raw data as a [channels x samples]
% vector in the 'data' input variable.
%
% Then, it computes bandpower features for the band specified
% in the 'band' input variable, which is a number between 0
% and 0.5, specifying center frequency in terms of the
% sampling rate.
%
```

(continued)

```
% As a last step, it applies the 'classifier' matrix to the
% features in order to obtain a single classification result
% for each sample. The 'classifier' vector specifies a
% classification weight for each processed channel.
%
% The result is a single classification result for each
% sample.
%
% This requires the Matlab signal processing toolbox.

% Design bandpass filters and apply them to the data matrix.
% The filtered data will contain bandpass filtered data as
% channels.
[n, Wn] = buttord(band*[0.9 1.1]/2, band*[0.7 1.4]/2,1,60);
[b, a] = butter(n, Wn);
processed_data = filter(b, a, data);

% For demodulation, rectify and apply a low pass.
[b, a] = butter(1, band/4);
processed_data = filter(b, a, abs(processed_data));

% Finally, apply the linear classifier.
class_result = processed_data * classifier;
```

Note that, to be viable in an online environment, an algorithm must operate on its signal in a causal way, i.e., it may not use future samples in order to process present samples. (A certain amount of non-causality may be possible by windowed operation on buffered data, although this will increase the effective delay between input and output data.)

Also note that the `classify()` function omits spatial filtering – in Matlab, this may be done easily by pre-multiplying the data with a spatial filter matrix if desired.

7.4.3 Transforming Matlab Code into BCI2000 Events

BCI2000 can execute Matlab code using the `MatlabSignalProcessing` module. For use with BCI2000, our Matlab code needs to be cast into a form that suits the BCI2000 filter interface. In this event-based model, which is very similar to that described earlier in this chapter for C++, portions of code are called at certain times to configure a filter component's internal state, and to act upon the signal in chunks on its way through the BCI2000 chain of filters.

7.4.3.1 Process

The most central event in the filter interface is the “Process” event. The “Process”
event handler receives a signal input, will process this input according to the filter
component’s role in the signal processing chain, and return the result of processing

in a signal output variable. It is important to understand that the “Process” handler
is called separately for each chunk of data, and thus does not see the signal in its
entirety. Also, the size of data blocks (chunks) is freely configurable by the user.
This implies that “Process” scripts may not depend on a certain data block size,
and will sometimes need to maintain their own data buffers when the algorithm
in question operates on windows of data rather than continuously. In the current
example, this is not the case, so we need not maintain an internal data buffer. Still,
we need to maintain an internal state between calls to the “Process” handler in order
to preserve the state of IIR filter delays. This will allow continuous operation on the signal with the same processing result as in the offline version of the algorithm.

The algorithm’s online version in the `bci_Process` script will thus be:

```
function out_signal = bci_Process( in_signal )

% Process a single block of data by applying a filter to
% in_signal, and return the result in out_signal.
% Signal dimensions are ( channels x samples ).

% We use global variables to store classifier,
% filter coefficients and filter state.
global a b z lpa lpb lpz classifier;

[out_signal, z] = filter( b, a, in_signal, z );
out_signal = abs( out_signal );
[out_signal, lpz] = filter( lpb, lpa, out_signal, lpz );
out_signal = out_signal * classifier;
```

7.4.3.2 Initialize

Determination of filter coefficients is part of per-run initialization, and occurs in the
“Initialize” event handler:

```
function bci_Initialize( in_signal_dims, out_signal_dims )

% Perform configuration for the bci_Process script.

% Parameters and states are global variables.
global bci_Parameters bci_States;

% We use global variables to store classifier vector,
% filter coefficients and filter state.
global a b z lpa lpb lpz classifier;
```

```
% Configure the Bandpass filter
band = str2double( bci_Parameters.Passband ) / ...
         str2double( bci_Parameters.SamplingRate );
```

```
(continued)
[n, Wn] = buttord(band*[0.9 1.1]/2, band*[0.7 1.4]/2,1,60);
[b, a] = butter(n, Wn);
z = zeros(max(length(a), length(b))-1, in_signal_dims(1));

% Configure the lowpass filter
[lpb, lpa] = butter(1, band/4);
lpz = zeros(max(length(lpa), length(lpb))-1, ...
      in_signal_dims(1));

% Configure the Classifier vector
classifier = str2double( bci_Parameters.ClassVector );
```

7.4.3.3 StartRun

In addition, we need to reset filter state at the beginning of each run, using the
“StartRun” event handler:

```
function bci_StartRun

% Reset filter state at the beginning of a run.

global z lpz;
z   = zeros(size(z));
lpz = zeros(size(lpz));
```

7.4.3.4 Constructor

To complete the Matlab filter code, we need to declare the “Band” and “Classifier”
parameters in a “Constructor” event handler:

```
function [ parameters, states ] = bci_Construct

% Request BCI2000 parameters by returning parameter definition
% lines as demonstrated below.

parameters = { ...
  [ 'BPClassifier float Passband= 10 10 0 % %' ...
       ' // Bandpass frequency in Hz' ] ...
  [ 'BPClassifier matrix ClassVector= 1 1 1 0 % %' ...
       ' // Linear classifier vector' ] ...
};
```

7.4.3.5 Preflight

Finally, we need to check parameters for consistency in a “Preflight” script, and
declare the size of our filter’s output signal:

```
function [ out_signal_dim ] = bci_Preflight( in_signal_dim )

% Check whether parameters are accessible, and whether
% parameters have values that allow for safe processing by the
% bci_Process function.
% Also, report output signal dimensions in the
% 'out_signal_dim' argument.

% Parameters and states are global variables.
global bci_Parameters bci_States;

band = str2double( bci_Parameters.Passband ) ...
         / str2double( bci_Parameters.SamplingRate );
if( band <= 0 )
  error( 'The Passband parameter must be greater zero' );
elseif( band > 0.5 / 1.4 )
  error( [ 'The Passband parameter conflicts with the ' ...
    'sampling rate' ] );
end

out_signal_dim = [ 1, size( in_signal_dim, 2 ) ];
if( in_signal_dim( 1 ) ~= ...
      size( bci_Parameters.ClassVector, 2))
  error( [ 'ClassVector length must match the input ' ...
    'signal''s number of channels' ] );
end
```

In addition to this tutorial, you can find more information about Matlab support
in Sect. 10.7.5.

Chapter 8
Exercises

The previous chapters provided descriptions of different aspects of the BCI2000 system, and gave tutorials for use of two different types of brain signals. In this chapter, we include a number of exercises that build on these descriptions. Each of these exercises addresses a different component of the system. The exercises are meant to be followed in order.

Chapters 3 and 10 give an overview and detailed description of the most important components of the BCI2000 system, respectively. We will here provide a realistic exercise that will touch on the key parameters of these components.

This exercise will simulate the configuration of a BCI system that implements a cursor task. Thus, all subsequent exercises assume the use of the `CursorTask_SignalGenerator.bat` batch file. We suggest to start with the `CursorTask_SignalGenerator.prm` parameter file and to change it appropriately as you go along. It is a good idea if you save the parameter file with a different name as you make changes.

To begin, start BCI2000 using the batch and parameter files listed above. You can press Set Config and Start. You will notice that you can control the cursor in the display using the mouse. The exercises in the following sections will reconfigure a number of components of the system. The cursor will follow the mouse again only when all configuration changes have been made.

8.1 Source Module

We begin with an exercise relating to signal acquisition. Thus, we will be changing
parameters in the Source tab of the BCI2000 configuration dialog.

Q: We assume that we are recording EEG signals from eight channels (C3,
Cz, C4, Cp3, Cpz, Cp4, Fpz, Oz) using a data acquisition (DAQ) device that has a sampling rate of 512 Hz. The whole system (i.e., including cursor movement)
should be updated 32 times per second. The DAQ device provides floating point
signals that are in units of μV. Which BCI2000 parameters need to be changed and
why?

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A: Because we are simulating acquisition at 512 Hz from eight channels, we need to set the parameters SamplingRate to 512 and SourceCh to 8, respectively. Because we know the names of the channels, we can enter them (delimited by spaces) in the ChannelNames parameter. This way, we can refer to channels by names when BCI2000 processes signals. Because the DAQ device gives floating point signals in microvolts, we need to set SignalType to float32 and SourceChGain to a series of ones (i.e., the conversion factor between the input signal from the DAQ device and µV is 1), respectively. Because there are eight channels, SourceChGain needs to be a series of eight 1's and SourceChOffset needs to be a series of eight 0's. (If very precise measurements are important, it may be important to determine the offset and gain of each channel using an external procedure and then to configure these two parameters with specific values determined from that procedure.) Because we would like to update the system 32 times per second, we need to set SampleBlockSize to 16 (i.e., 512 samples per second divided by 32 updates per second equals 16 samples per update/block).

At this point, you can click on Set Config and then Start. You will notice a window labeled Source Signal with simulated EEG. The simulated EEG consists of noise and sine waves whose amplitude responds to mouse movements. Notice that the channel labels correspond to the channels you defined. You should also see the simulated EEG and the cursor movement updating smoothly. Also notice that in the Timing window, the two bottom-most lines (i.e., Roundtrip and Stimulus) reach up to a sizable part of the upper-most trace (i.e., Block). This means that it takes the system a good portion of one block to process that block and to update the display. In this respect, note that one block only corresponds to 31.25 ms

16 (=SampleBlockSize) ms

BlockSize to 128, set the configuration again and start. You will notice that the
Source Display and cursor movement are much choppier (since the display is only
updated four times per second (128)), but that now the Roundtrip and Stimulus
traces in the Timing window only capture a very small portion of the Block
trace.
In other words, the Timing window gives a simple view of how taxed the computer
is with your particular BCI2000 configuration. This is determined by the perfor-
mance of your computer (in particular, CPU speed, number of processors/cores, and
graphics card performance) and the complexity of the BCI2000 configuration (i.e.,
block size, sampling rate, number of channels, and the demands of signal processing
and visual display). One common situation is that the visual display begins to con-
sume substantial processing cycles at higher sampling rates. Thus, if the Roundtrip
and Stimulus traces get closer to or even exceed the Block trace, you may want
to increase VisualizeSourceDecimation in the Visualization tab. Set the parameter
SampleBlockSize back to 16.

Q: In this exercise, we will use the mouse to modulate the amplitude of a sine
wave at C3 and C4 at 18 Hz. This simulates a subject that can modulate the am-
plitude of a sensorimotor rhythm at these locations and that frequency. With our
BCI, we would like to control a computer cursor using one or both of these signals.
Which BCI2000 parameters need to be changed and why?

A: As described, we want to simulate a sine wave at channel C3 (channel 1) and C4 (channel 3) at 18 Hz. Thus, we will set parameters SineChannelX to 1, SineChannelY to 3, and SineFrequency to 18 Hz, respectively. We also make sure that ModulateAmplitude is checked. Set the configuration and start. Notice that the sine wave at channels 1 (C3) and 3 (C4) will respond to horizontal and vertical mouse movements, respectively.

8.2 Signal Processing Module

In the next part of the exercise, we will be extracting the simulated signals (i.e., amplitude of the sine waves) at C3 and C4 and 18 Hz in real time and will be using it for cursor control. To do this, we will have to deal with at least four components of Signal Processing, i.e., the Spatial Filter,theAR Filter,theLinear Classifier, and the Normalizer. The following exercises address these three components.

Q: Spatial filtering can substantially improve the results of feature extraction in EEG-based BCIs [3]. Thus, while not necessary for our simulated example, we will apply a Common Average Reference (CAR) filter. This filter subtracts the average of all other channels from a particular channel.[1] In our example, in which we expect signals at channels C3 and C4, we would thus create two output signals that each have the average of all other channels subtracted. This can be done using the Spatial Filter. Which configuration changes are necessary?

A: Two changes are necessary. The first configuration change ensures that all eight channels are being transmitted to the Signal Processing module. By default, not all channels are being submitted to Signal Processing to reduce processing demands. Which channels are transmitted is defined by the parameter TransmitChList in the Source tab. Because we would like to transmit all eight channels, this parameter needs to be set to 1 2 3 4 5 6 7 8 . Thus, there are eight channels available to the Signal Processing module, which are identical to the eight acquired channels.

The second configuration change implements a spatial filter with the desired

characteristics. As described, we would like to subtract from C3 or C4 the average of all the other channels to yield the filtered channels C3f and C4f. Thus, this can be written as `C3f=C3-(Cz+C4+Cp3+Cpz+Cp4+Fpz+Oz)/7` and `C4f=C4-(C3+Cz+Cp3+Cpz+Cp4+Fpz+Oz)/7`.Given $\frac{1}{7} = 0.14$ and reformatting for the order of the channels in the list of transmitted channels, this gives the following spatial filters:

```
C3f=1*C3-0.14*Cz-0.14*C4-0.14*Cp3-0.14*Cpz-0.14*Cp4-0.14*Fpz-0.14*Oz,
```

[1]Some scientists would subtract the average of all channels when calculating the CAR filter. It is not clear whether one version of that filtering technique is generally better than the other.

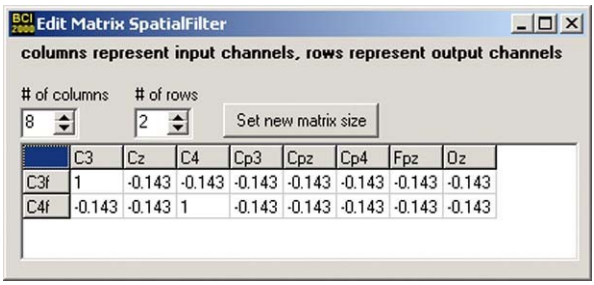
Edit Matrix SpatialFilter
columns represent input channels, rows represent output channels
# of columns
# of rows
8
2
Set new matrix size
C3 Cz C4 Cp3 Cpz Cp4 Fpz Oz
C3f 1 -0.143 -0.143 -0.143 -0.143 -0.143 -0.143 -0.143
C4f -0.143 -0.143 1 -0.143 -0.143 -0.143 -0.143 -0.143

Fig. 8.1 The spatial filter matrix for this example

and

```
C4f=-0.14*C3-0.14*Cz+1*C4-0.14*Cp3-0.14*Cpz-0.14*Cp4-0.14*Fpz-0.14*Oz.
```

In other words, the spatial filter defined by the matrix shown in Fig. 8.1 takes input from all eight transmitted channels (which in this example are identical to the acquired eight channels, but do not have to be) and produces two output signals labeled C3f and C4f. Thus, all further processing is done on only two channels where the first channel represents the spatially filtered version of C3 (which was the first acquired channel and the first transmitted channel), and the second channel represents the spatially filtered version of C4 (which was the third acquired channel and the third transmitted channel). Because the input of the spatial filter is the list of transmitted channels, the number of columns in the SpatialFilter matrix has to equal the number of transmitted channels specified in TransmitChList.

Q: Once the signals are spatially filtered, we need to convert them into the frequency domain, i.e., to calculate a spectrum. Once we have derived a spectrum, we can extract the signal at 18 Hz that we know is represented in the signal. For reasons described elsewhere [2], the most commonly used spectral estimation routine in BCI2000 is the Maximum Entropy Method (MEM) method [1] rather than, for example, the Fast Fourier Transform (FFT). The parameters corresponding to the MEM method are listed in the ARFilter section of the Filtering tab. Which parameters of this section, if any, need to be changed and why?

A: No parameters in this section need to be adapted. With the settings in this parameter file, a spectrum is calculated between 0 and 30 Hz in 3 Hz bins. This spectrum is calculated based on the previous 0.5 s, which is a reasonable compromise

between accuracy and group delay. The preselected model order is 16. For EEG,
good values are 16–20, whereas for ECoG, good values are 20–30. In either case,
the output of the ARFilter component consists of two channels of spectra that correspond to the spectra for C3f and C4f. Each of the two spectra consists of 11 bins that reflect the frequency estimates at 0, 3, 6, 9, 12, 15, 18, 21, 24, 27, and 30 Hz. The
next task is to translate these estimated frequency amplitudes into usable outputs for
cursor control.

Q: The next step is to select from these features (i.e., amplitudes at given locations and frequencies) the linear combination of features that represents the signals

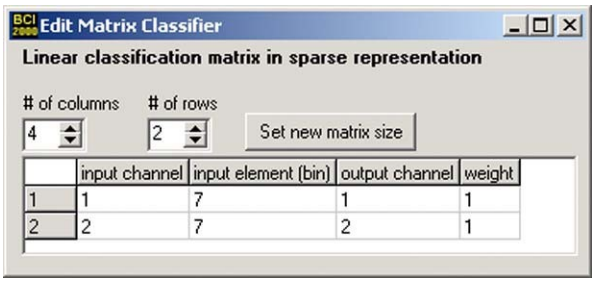

Fig. 8.2 The Classifier parameter for this example

of interest. In this case, we know that the signals of interest are the amplitudes at
C3 and C4 at 18 Hz. We also know that activity at C3 corresponds to horizontal
movement of the mouse and activity at C4 corresponds to vertical movement of the
mouse. Given that we would like the same mapping for control of the cursor, which parameters need to be changed and how?

A: The relevant parameter is Classifier in the Filtering tab. As described above, the signals of interest are located at C3 (i.e., spatially filtered channel 1) and C4 (i.e., spatially filtered channel 2) at 18 Hz (i.e., bin 7 in the computed spectra). Thus, we
would like to associate channel 1, bin 7, with control signal/output channel 1 (which
is used as horizontal velocity in the CursorTask); and we would like to associate channel 2, bin 7, with control signal/output channel 2 (which is used as vertical
velocity in the CursorTask). The full configuration is shown in Fig. 8.2. As an alternative to using channel and bin numbers, it is also possible to enter channel
names and frequencies (i.e., C3f/C4f and 18 Hz, respectively).

This is a simple example for a classifier that makes use of only two features.
More complex classifiers could be designed (perhaps using an automated routine
offline) and then used. In such a situation, there will likely be a linear combination of features rather than just one like in this example. In this case, the resulting
control signal/output channel values are linear combinations of the corresponding
feature values multiplied with the weight (defined in the right-most column) for
each feature.

Now it is a good time to save your parameter file. Then, when you set the configuration and start the system, you should position the mouse on the appearing targets.
After several trials, the system will begin to appropriately react to the mouse move-

ments. This is because the system has to adapt to the control signal values produced by the classifier you just designed. The function of this adaptation routine is discussed in the next exercise.

Q: For this exercise, let's change the weights of the first and second control signal. To do this, enter 5 and 2 in the first and second row and in the rightmost column in the parameter Classifier in the Filtering tab, respectively. Set the configuration and start. What happens and why?

A: For the first couple of trials, the cursor automatically moves to the top right of the window. This is because we set the weight of the first and second control

signal (which correspond to horizontal and vertical movement in the cursor task,
respectively) to 5 and 2, respectively. Thus, the output of the Signal Processing
module became five times larger for the horizontal movement signal and two times
larger for the vertical signal. We will discuss below how BCI2000 adapts to this
change in signal dynamics.

Q: One substantial problem in BCI operation is that the control signal dynamics
(e.g., their minimum, maximum, mean, or standard deviation) are initially unknown
and may also change over time. This presents a problem for online operation that
needs to appropriately use these signals for a particular function, e.g., to control a
cursor. As an example, the amplitude of a particular brain signal may change be-
tween 10 and 100 on one day, and between 100 and 300 the following day. Thus, in
order to effectively use these control signals, they have to be normalized. For exam-
ple, they should have zero mean and unit variance. How could this be accomplished
given that we do not know much about these signals ahead of time?

A: One pragmatic and effective way to tackle this problem is to estimate the
control signal mean o and standard deviation s from the control signal c derived
online, and then to normalize each control signal by these values, e.g., using the
following equation: $c = (c - o)/s$. In BCI2000, these values for o (offset) and
g := 1/s (gain) are represented by the parameters NormalizerOffsets and Nor-
malizerGains, respectively. Thus, the Normalizer component in the BCI system
subtracts from each control signal, which in itself results from application of the
Classifier matrix, the corresponding value (e.g., the second entry for the second
control signal) of the NormalizerOffsets parameter, and multiplies the result with
the corresponding value of the NormalizerGains parameter.

Q: Can you think of a few different approaches to estimating these offset and
gain parameters from the data acquired in real time? Which approaches could you
use for the following two scenarios: in scenario 1, you know something about the
desired task. For example, you may know that there are four targets on the
screen

(like in the cursor task examples used in these exercises), and you also know what
target the cursor should move towards. In scenario 2, you do not know anything
about the task, e.g., like in an imaginary wheelchair application in which the user
could move toward any target.

A: In scenario 1, we could simply estimate the dynamics of the control signal
values for each target separately, e.g., calculate the mean and variance for the left
and right target, and average them between the two targets to determine the offset
(mean) and gain (1/standard deviation) for the horizontal control signal. The same
procedure could be applied for the top and bottom target to determine the offset
and gain for the vertical control signal. Knowing about the correct task category
(i.e., target) has the advantage that we can get a good estimate of offsets and gain
relatively quickly, and that it will be correct even if the target frequencies are not
the same (e.g., in case the left target appears twice as often as the right target).
The disadvantage is that in a real-world application (i.e., scenario 2), we will not
know what the desired target is at any given point in time. In this case, we can only
estimate control signal parameters from all control signal values, i.e., assuming that

the control signal mean over time should be zero. This implies that we will need to use a longer period for that estimation (since it may be possible that just by chance we could move to the left five times in a row), and that we would not be able to appropriately adapt in a scenario in which one direction is always chosen more often than another. The adaptation concept in BCI2000 can actually accommodate both situations. Please see Sect. 10.6.6 for a detailed description.

Q: If you use the standard `CursorTask_SignalGenerator.bat` batch file, and `CursorTask_SignalGenerator.prm` parameter file, you can control the cursor using your mouse. This functionality was used earlier in this section to demonstrate different signal processing aspects in BCI2000. If you control the cursor using your mouse, you will notice that there is a small delay between when you move the mouse and when the cursor starts moving. What causes this delay? (Hint: this delay is not due to slow processing or screen update.)

A: In this configuration, the movement of the mouse is modulating the amplitude of a sine wave around 10 Hz. Signal processing then extracts this signal by computing a spectral analysis. Any spectral analysis has to be performed on a particular time window, which in the AR Signal Processing filter is governed by the WindowLength parameter. By default, this window length is set to 500 ms. In other words, a particular movement will not immediately affect the output, and will have a maximum effect on the output 500 ms later (assuming the movement lasted for the whole 500 ms). Thus, this delay is intrinsically caused by the carrying signal (a 10 Hz oscillation), and the procedure to extract that signal. It is important to realize that, on a typical machine, this delay will be dramatically longer than any delay caused by BCI2000 signal processing or feedback/screen update.

References

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2. McFarland, D.J., Lefkowicz, T., Wolpaw, J.R.: Design and operation of an EEG-based brain-computer interface (BCI) with digital signal processing technology. Behav. Res. Methods Instrum. Comput. 29, 337–345 (1997)
3. McFarland, D.J., McCane, L.M., David, S.V., Wolpaw, J.R.: Spatial filter selection for EEG-based communication. Electroencephalogr. Clin. Neurophysiol. 103(3), 386–394 (1997)

Chapter 9
Frequently Asked Questions

9.1 Timing Issues

Q: The signal traces in the source signal display, or the feedback cursor in the application display, is not updated at a constant speed, but rather appears jumping.

A: In the timing display window (enable in the Visualize tab if not shown), check whether block duration (the top curve) is constantly at the level indicated by the tick mark to the left. When this is not case, try the following:

- Increase the value of the Source Decimation parameter on the Visualize tab to reduce the processor load associated with the source signal display.
- Increase the value of the SampleBlockSize parameter to reduce the system update rate.

9.2 Startup

Q: When clicking Set Config, I get error messages for each of the modules such as: `EEGSource: Could not make a connection to the SignalProcessing Module` and `Application: SignalProcessing dropped connection unexpectedly.`

A: This may be caused by the Microsoft TV\Video Connection in Network Connections, if you have it. To remedy this:

1. Right-click on My Network Places,
2. Select Properties,
3. Right-click on Microsoft TV\Video Connection,
4. Select Properties,
5. Uncheck Internet Protocol,
6. Click OK.

Q: When I start the gUSBamp source module, I get the error message: `Cannot find ordinal 37 in dynamic library gUSBamp.dll`.

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A: Most likely, your gUSBamp source module finds an incompatible version of the `gUSBamp.dll` driver library. Make sure that, in the directory where `gUSBampSource.exe` resides (i.e., usually the `prog` directory), or in the `\windows\system32` directory, there is a file `gUSBamp.dll` in the exact version that matches the gUSBamp driver.

Q: The BCI2000 gUSBamp source module does not recognize my g.USBamp amplifier. When I click Set Config, I get the an error message:

```
gUSBampADC::Preflight: Could not detect any amplifier.
Make sure there is a single gUSBamp amplifier connected
to your system, and switched on.
```

A: Make sure that the amplifier is attached, switched on, and that it works with g.tec's demonstration program.

9.3 Feedback

Q: The first time a subject is run using the cursor feedback protocol, and during the first few trials of the first run only, the cursor moves to the top of the screen and does not respond to user input.

A: This is not so much a bug as a side effect of the way the adaptation mechanism works. Since the adaptation mechanism hasn't been trained, all it has are the initial values for offset and gain. For each subject, it will take a few trials to adapt BCI2000 to this subject's signals.

Therefore, you will typically save a subject's adapted parameters after each session, and use this as a starting point for the next session. Alternatively, you may load a subject's parameters from a previous session's `data` file by specifying the data file rather than a parameter file from the `Load Parameters...` dialog.

9.4 Replaying Recorded Data

Q: Rather than controlling BCI2000 from a brain signal, I would like to use a recorded data file as input. Is there a kind of "replay mode" in BCI2000?

A: While this could easily be done, e.g., by writing a source module that reads from a file, we have not done this, and this is for at least two reasons:

First, if the version of BCI2000 that you are using is not the exact same as the one that was used to record the data, and/or you change some system parameters,

then, depending on the experimental paradigm, results may be undefined. E.g., in a
2D cursor task, what should happen if you slow down the cursor such that the cursor has not yet reached a target when in the original data file it has (i.e., and the trial is
over)?

Second, scientifically it is a bad idea to “simulate” online performance by loading a single datafile, changing a few parameters, and seeing how it would have worked. If you are interested in evaluating the effect of different signal processing routines,

you should write your own offline analysis routine that uses statistical analyses,
together with a comprehensive body of data, or you need to run comprehensive
online studies.

Of course there is nothing in the code that would prohibit you from writing your own such module, but you should note the two caveats above.

9.5 Random Sequences

Q: Is there a way to obtain the same random sequence each time BCI2000 is
run? I don't care about the sequence itself, it should just be the same each time.

A: The SignalGenerator source module has a parameter, RandomSeed, that determines the pseudo random number generator's seed value. If this parameter is
zero, the generator will be initialized from the system timer.

While absent from other BCI2000 modules by default, each component that uses the BCI2000 pseudo random generator will behave according to this parameter if
it is present. To introduce the RandomSeed parameter into a module that does not
provide the RandomSeed parameter, use `--RandomSeed=10` as a command line option to that module when starting up BCI2000. Note that the parameter will have
the same value across all modules (10 in the example), and it will appear on the
System tab in the operator module's parameter dialog.

9.6 Visual Stimulation

Q: Is visual stimulation synchronized with screen refresh (vertical blanks)?

A: BCI2000 does not synchronize its video output with refresh cycles to avoid interference with its own timing. We have run comprehensive evaluations
that demonstrated that with CRT monitors that are set to high refresh rates
(e.g., >100 Hz) and with appropriate computer power, the latency jitter in the
BCI2000 system (i.e., from data acquisition to stimulus presentation) is less than
10 milliseconds with even smaller jitter. This timing behavior can support a large
fraction of all BCI experiments. For more information about BCI2000 timing, please check out [1].

If you feel that output should be synchronized, and have access to the BCI2000
source code, adding a DirectDraw `WaitForVerticalBlank()` call immedi-

ately before the Task filter's call to `UpdateWindow()` at the end of its `Process()` function should help.

Q: The Stimulus Presentation program only allows for either a random sequence of stimuli, or a deterministic sequence of stimuli. In my experimental paradigm, I would like to present random stimuli, but have them interspersed by a particular resting stimulus. It looks like BCI2000 does not support that?

A: BCI2000 can present any sequence of stimuli. Referring to the example above, where stimulus 1 may be the resting stimulus and stimuli 2–9 are to be randomly presented, the following could be a valid sequence: 1 3 1 2 1 9 1 8

1 5 1 6 . Such a sequence could be determined using an external procedure, and
then BCI2000 could be configured using that particular sequence. Specifically, it
would be possible to write a Matlab program similar to the one below.

```
num_values = 9;
r = round(rand(1, num_values)*num_values+1);
fp = fopen('fragment.prm', 'wb');
fprintf(fp, 'Application:Sequencing intlist ' ...
              'Sequence= %d', num_values*2);
for i = 1:num_values
 fprintf(fp, ' 1 %d', r(i));
end
fprintf(fp, '11%% / /test parameter\r\n');
fclose(fp);
```

Execution of that Matlab program produces a parameter file fragment
`fragment.prm`. When loaded on top of a full parameter file, this would produce a random sequence. This process can be fully automated using BCI2000 batch files,
scripting, and command line parameters (see Sect. 6.2) so that clicking on one icon
could run that Matlab program, execute BCI2000, load a full parameter file, load the parameter file fragment (containing the randomized sequence) produced by Matlab,
set the configuration, and start operation.

Q: I would like to control the Cursor Task in BCI2000 using a joystick or a mouse, e.g., to implement a standard center-out paradigm. How do I do that?

A: As is so often the case, there are different ways of accomplishing a particular goal. In this case, it would be possible to change the source code of the Cursor Task such that it would be controlled by, for example, a joystick. However, BCI2000 supports a solution that is much more elegant and powerful. This solution is based on
the Expression Filter described in Sect. 10.7.4. Cursor movement in the Cursor Task is controlled by the first and second control signal produced by the Signal Processing module. Typically, this control signal is controlled by the brain signals that are result of the Linear Classifier (see Sect. 5.2.4.2 or Sect. 10.6). These resulting control signals are passed through the Expression Filter where they can be modified using
an algebraic expression. This algebraic expression has access to BCI2000 states,
and joystick position can easily be logged in states using the `--LogJoystick=1` command line option when starting up the Source Module. Thus, first, logging of
joystick position needs to be enabled using that command line option. Then, the Expression Filter needs to be configured to simply replace the first and second control
signals by the states that represent joystick position. This is accomplished by simply
setting the parameter Expressions to the following 2-by-1 matrix:

```
JoystickXpos
JoystickYpos
```

By modifying the simple expression shown above, it would also be easy to use a
combination of classified brain signals and states to drive an output such as the Cursor Task. You can find more information about the Expression Filter in Sect. 10.7.4.

References

1. Wilson, J.A., Mellinger, J., Schalk, G., Williams, J.: A procedure for measuring latencies in brain-computer interfaces. IEEE Trans. Biomed. Eng. (in press)

Part II
Technical Reference

Chapter 10
Core Modules

10.1 Operator

The operator module is the user interface seen by the experimenter. It makes it possible to view and edit system parameters, save and load parameter files, and to start and stop system operation.

10.1.1 Starting BCI2000

In addition to the operator module, a running BCI2000 system also consists of three core modules that must be started up together with the operator module. These core modules realize data acquisition, signal processing, and application. They can be started in two ways:

1. Using the batch scripts in the `BCI2000/batch` folder – choose one of the available scripts, or modify one to fit your needs. Script files provide an easy way to customize BCI2000 behavior using command line options, which are described in Sect. 6.3.1.
2. Using BCI2000Launcher. This tool provides a graphical user interface for module selection, and allows for automated loading of parameter files at startup.

10.1.2 Main Window

The main window shown in Fig. 10.1 contains four large buttons. These buttons correspond to the tasks that need to be performed during an experiment:

- Config: opens the configuration window,
- Set Config: applies the current set of parameters to the system,
- Start: starts system operation,

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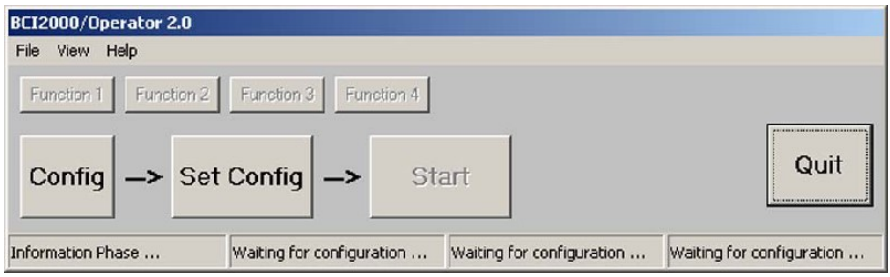

Fig. 10.1 The Operator module's main window

- Quit: exits the system once the experiment has finished.

Not all buttons are functional all the time; availability of a function depends on the state of the system. On top of the window, there are four function buttons (labeled Function 1–4) that execute Operator Scripts. Scripts and button captions may be configured freely from the preferences dialog. The status area, at the bottom of the main window, contains four fields. System status is displayed on the left, and module status is displayed in the three rightmost fields, in the natural order of core modules (i.e., Data Acquisition, Signal Processing, and Application).

10.1.2.1 Menus

The main window of the Operator module has three menus: File, View, and Help.

File Menu The File menu contains the following entries:

- Preferences: opens the Preferences dialog (see Fig. 10.2).
- Exit: terminates BCI2000 after displaying a confirmation message. This menu entry is always available, even if the Quit button is not enabled.

View Menu The View menu contains the following entries:

- States: displays a window that lists the state variables currently available in the system.
- Operator Log: toggles visibility of the log window. The log window is automatically opened when there are error or warning messages. You can display this window manually to view informative messages and debugging output.
- Connection Info: toggles visibility of the connection information window. This window displays information regarding whether connections between operator and core modules are established, network addresses, and the number of internal communication messages that have been transferred so far.

Help Menu The Help menu contains the following entry:

- About: displays extensive information about the operator module’s version number. This includes the source code revision it was built from, and the time of the build.

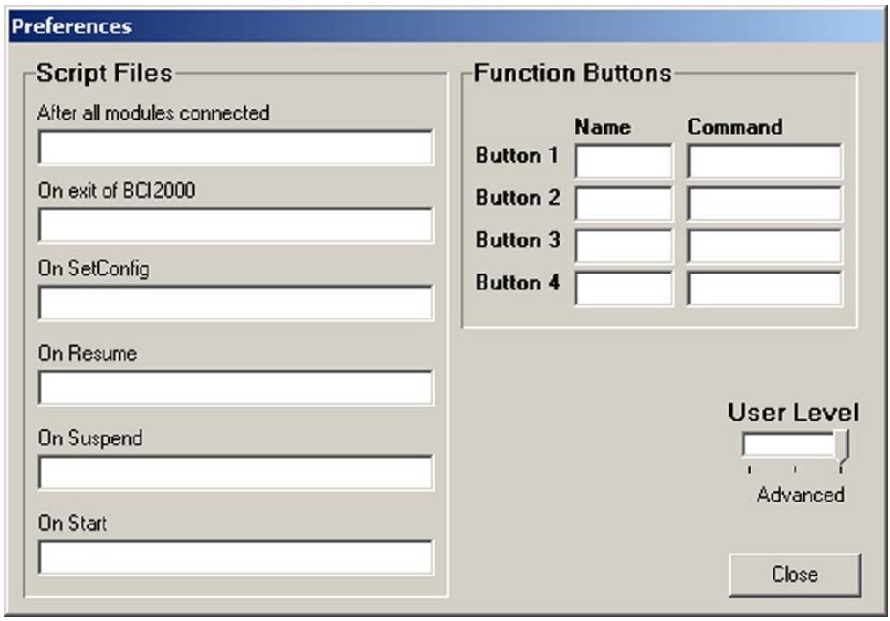

Fig. 10.2 The Preferences dialog

information is also kept inside the OperatorVersion parameter on the system
tab, and written into data files along with all system parameters.

- Help: Opens a web browser window with the BCI2000 help system displayed.

10.1.2.2 The Preferences Dialog

On the left side, the preferences dialog allows you to associate operator scripts with events, and on the top right, you may configure the main window's function buttons
using operator script commands. Please see Sect. 6.3.1 for scripting details. Scripts
may also be specified from the command line at startup.

On the bottom right, you may specify the global User Level to be one of begin-
ner, intermediate, o radvanced. When the user level is set to advanced, a slider control is displayed for each individual parameter in the Parameter Configuration
Dialog showninFig.10.3. Each parameter is shown only when its user level is equal to or below the global setting. Thus, this feature allows to simplify the configuration
dialog for less experienced users, or for your own convenience, in situations where
full access to configuration options is not necessary. As a typical example, once you have configured a stimulation experiment, you may only need to change the Sub-
jectName and SubjectRun parameters. Setting these two parameter's user levels to

beginner, and leaving the other’s at advanced, you may now switch the global user level to beginner, and will only see the two selected parameters displayed in the
configuration dialog.

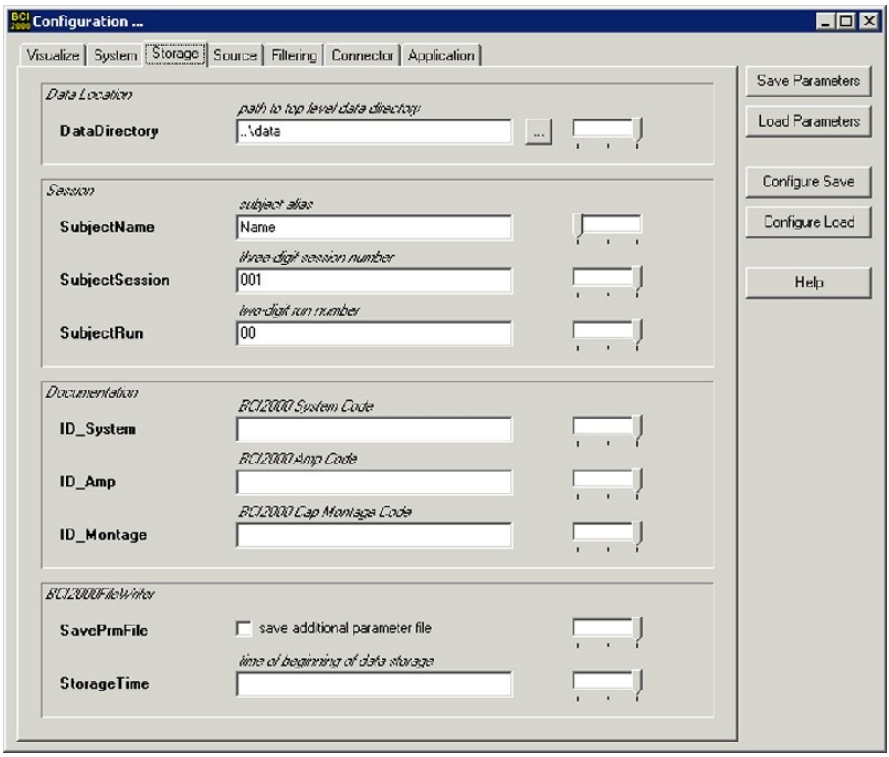

Fig. 10.3 The Parameter Configuration window

10.1.3 Parameter Configuration Window

The Parameter Configuration window is accessed by pressing the Config button in the main window. On the left side, this window displays a number of register tabs that correspond to parameter sections. Clicking on a tab will display the parameters from the corresponding section. Within a section, parameters are grouped according to subsections. In most cases, subsections correspond to individual filters (i.e., subcomponents of each module); however, filters with a large number of parameters might choose to group them into subsections to facilitate configuration. Within subsections, the order of parameter display depends on the order in which they are defined in the source code of the corresponding filter.

For parameters that hold one or more values, an edit field allows the user to change these values. For multiple values, entries are separated by a white space. If you would like to include values that contain white spaces, use “%20” (without the

quotes) instead of those white spaces.

For some parameters, drop-down menus, checkboxes, or chooser buttons are displayed to make it more convenient for the user to enter parameter values. Matrix-valued parameters display a button to load or save a matrix in ASCII format, and an Edit button that opens up a Matrix Editor window.

On the right side, there are five buttons, Load Parameters, Save Parameters, Configure Load, Configure Save, and Help. The current settings in the Configuration Window can be saved to a BCI2000 parameter file (`.prm`) for future use with Save Parameter. The Load Parameter button opens a dialog to load either a parameter file (`.prm`) or data file (`.dat`). When you load a parameter file, the Configuration Window is filled with the parameter values of that parameter file. When you choose a data file, the Configuration Window is filled with the parameter settings that were used to record that data file. The latter possibility is useful to replicate the settings from a particular experiment.

It is important to note that the number and names of parameters in the parameter/data file do not exactly have to match those in the currently running BCI2000 implementation. As an example, the currently running BCI2000 implementation may be using a source module that realizes acquisition from device X (with some parameters that are specific to that device X), whereas the parameter file may have been created with a BCI2000 implementation that used a source module for device Y, and corresponding parameters whose names may be different than those for device X. In such a case, BCI2000 simply applies those parameters in the parameter/data file that are also present in the currently running BCI2000 implementation, ignores those that exist in the parameter file but not in the running BCI2000 implementation, and does not change those that exist in the currently running BCI2000 implementation but not in the parameter file. This feature is extremely useful when replicating settings from a different BCI2000 implementation (e.g., one with a different acquisition device). It also allows the use of so-called “parameter fragments.” Parameter fragments contain only a subset of all parameters. For example, they may contain parameters that configure a data acquisition device for acquisition from a particular number of channels, or parameters that configure stimulus presenta-

tion for dual- or single-monitor configuration, etc. Because such fragments contain only a subset of all parameters, they are typically loaded on top of a full parameter file. You can create a parameter fragment by simply saving a parameter file, and then using a text editor to delete all parameters except those you would like to include.

Behavior of the load/save operation may be fine-tuned using the Configure Load and Configure Save buttons (Fig. 10.4). Each of these functions displays a list of parameter names and allows the user to select parameters that should be ignored during load/save operations. Thus, these functions essentially provide a different way to load/save parameter file fragments.

The parameter configuration window can also provide help to different parameters. When you click on the Help button, the mouse cursor changes into a question mark. Then, a click on a parameter name or edit field will open the appropriate help page when available. This help button is available only when a recent version of the BCI2000 `doc` directory is present along with the `prog` directory where the operator module resides.

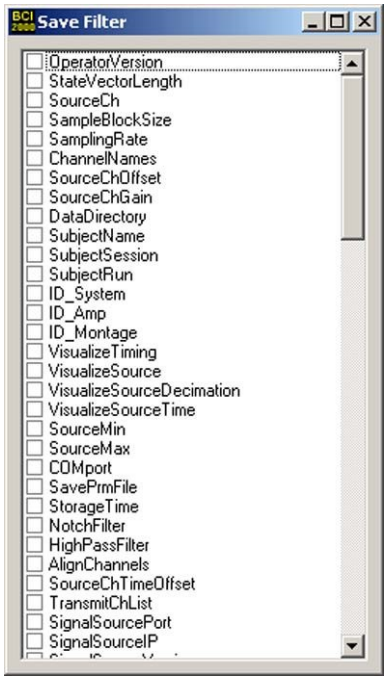

Fig. 10.4 The Save (or Load) Filter

10.1.4 Matrix Editor Window

In BCI2000, certain parameters have values that are described as a matrix, i.e., they consist of values that are organized into rows and columns. In addition, individual matrix entries may be matrices themselves, allowing for multi-level nested configuration matrices. The matrix editor (see Fig. 10.5) allows you to:

- Modify the values in matrix-valued parameters by clicking an entry to edit it.
- Change the size of the matrix by changing the “number of rows” or “number of columns” fields, and clicking the “Set new matrix size” button.
- Edit row and column titles (labels) by right-clicking the matrix and choosing “Edit Labels” from the context menu to switch into label editing mode.
- Convert matrix entries into sub-matrices and back into single entries – use the context menu’s “Convert to sub-matrix” and “Replace by single cell” items.
- Open another matrix editor to edit the contents of a sub-matrix – use the context menu’s “Edit sub-matrix” item.

10.1.5 Visualization Windows

Visualization windows may be moved and resized; BCI2000 remembers their
positions across sessions. When you right-click on a visualization window (see
Fig. 10.6), a context menu will appear. It has several options that include:

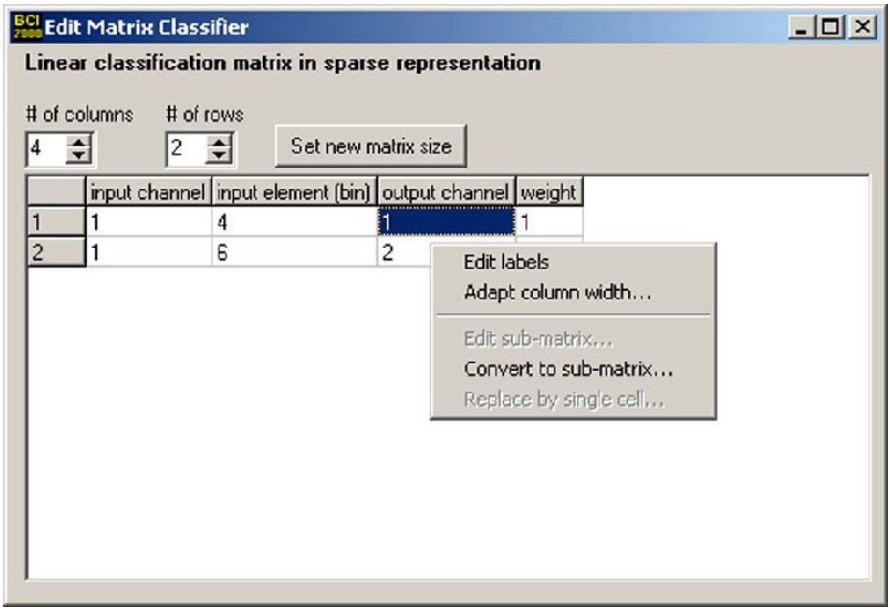

Fig. 10.5 The Matrix Editor window

- adjusting signal amplitude (enlarge/reduce signal),
- adjusting the time interval displayed in the window (fewer/more samples),
- choosing the number of signals displayed (fewer/more channels),
- switching between signal display as lines, and colored blocks (“display mode”),
- choosing signal colors,
- switching signal baselines, and unit display on and off,
- applying highpass, lowpass, or notch filters to the displayed signal.

For signal visualizations, the arrow keys and page up/page down keys may be used to scroll through channels. The full set of keyboard shortcuts is given in Table 10.1.

When the signal’s physical unit is displayed, it is represented as a white bar (Fig. 10.7). In the example in this figure, there are white markers above and below the bar. These markers indicate the range corresponding to the value written in the bar. These markers may be missing; then the range corresponds to the height of the bar itself.

Finally, the physical unit may be displayed with a white marker attached to the bar (Fig. 10.8). This display is used for nonnegative signals. Here, the physical unit corresponds to the distance of the white marker to the signal’s baseline.

Clicking Choose Signal Colors... from the context menu will open up a color dialog. This dialog has a field “Custom colors.” The list of colors in this field defines the colors of the signal channels and is terminated with a black entry. Signal colors

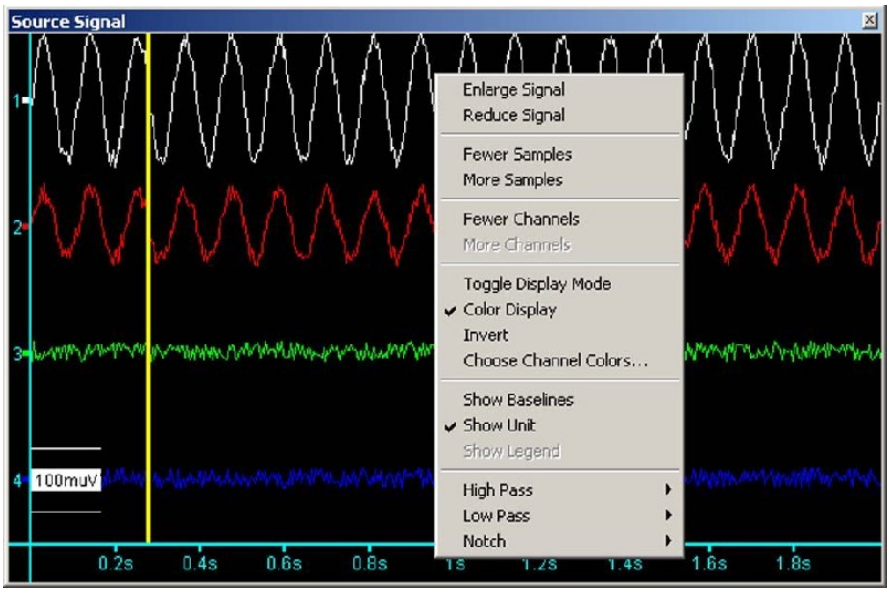

Fig. 10.6 A visualization window

Table 10.1 Keyboard shortcuts

`up/down`	Back/forward one channel
`page-up/page-down`	Back/forward one screenful of channels
`-/+`	Reduce/enlarge the signal
`,/.`	Fewer/more channels
`left/right`	Slow down/speed up the time sweep
`home/end`	Jump to the first/last screenful of channels
`typing a number and pressing return (or 'g')`	Jump to the specified channel number

are taken from these fields in the order in which they appear; when there are more signals displayed than colors defined, colors will be re-used in order.

10.2 Filter Chain

Each of the three BCI2000 core modules contains a chain of filters, i.e., a sequence of filters that form a filter chain. Each filter accepts data (e.g., raw brain signals) as input and produces an output (e.g., brain signal features).

Each filter produces an output each time it receives an input. That output is then automatically submitted to the subsequent filter for processing. This is analogous to a water pipe: unlike a water stream, it is impossible to insert or remove water from

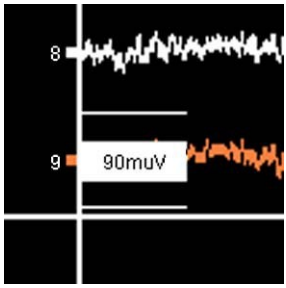

Fig. 10.7 The signal's physical unit is displayed inside a white bar,with markers above and below corresponding to the value written in the bar

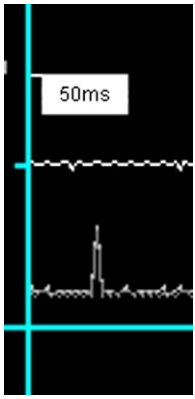

Fig. 10.8 In this example, a white marker is attached to the unit's bar. The distance from 0 (i.e., in this case the x-axis) corresponds to the value written in the bar

inside the pipe without breaking it. Similarly, although signal portions may change their shape on their way through the pipe (filter chain), it is impossible to insert or remove any of them. Thus, each data portion acquired by the data acquisition module will run through the entire BCI2000 system where it is processed by a sequence of filters.

10.3 Data Acquisition Filters

The source module contains several filters that handle data acquisition and storage, signal conditioning, and transmission to the signal processing module. These functions are realized by the DataIOFilter, AlignmentFilter, and TransmissionFilter, respectively (Fig. 10.9). The DataIOFilter realizes four functions: (1) data acquisition, which is implemented by an ADC filter; (2) data storage, which is realized

by one of several FileWriter filters that support different data formats; (3) signal
calibration into physical units (typically, µV); and (4) visualization of the acquired
(brain) signals.

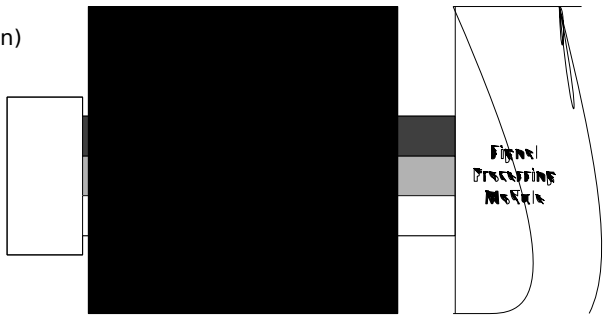

Fig. 10.9 Filters in the source (i.e., data acquisition) module

10.3.1 DataIOFilter

The DataIOFilter is part of every source module, and manages data acquisition, storage, and signal calibration into physical units (µV). For data acquisition, the DataIOFilter interfaces to an ADC component present inside a source module. For actual data storage, the DataIOFilter uses one of multiple FileWriter components present in a source module.

10.3.1.1 Parameters

Generally, data acquisition parameters are used for analog/digital (i.e., A/D) hardware configuration. Ideally, A/D hardware is configured by the ADC component; and thus, configuration changes to the hardware can simply be done by changing the parameter values in the Operator's config dialog. If the software interface to the A/D hardware does not allow for hardware configuration, actual A/D configuration must be done manually, and data acquisition parameters in the Source module have to be set to the same values. The following parameters are present in all BCI2000 Source modules, irrespective of the hardware device it supports:

ChannelNames A list of textual labels that are associated with channels. For EEG recordings, channel names should be electrode positions according to the 10–20 system (Fz, CPz, CP3, ...). While not mandatory, providing labels is a means to document recording locations in the data file itself, so that this information does not need to be maintained externally (e.g., in a lab notebook). Also, BCI2000 makes it

possible to refer to channels by their labels. Thus, channel labels make it easier to avoid errors in configuring feedback parameters.

DataDirectory Path to an existing directory. Recorded data will be stored below that directory. The path may be absolute, or relative to the source module's working directory at startup. Usually, the working directory at startup is the `prog` directory.

ID_System, ID_Amp, ID_Montage These parameters are provided for documentation purposes (i.e., of the system, amplifier, and montage, respectively) and may contain arbitrary text.

SampleBlockSize The number of sample points that make up a BCI2000 sample block. The temporal duration of such a sample block is given by the ratio of
SampleBlockSize to SamplingRate, and determines timing resolution for feedback.

SamplingRate The number of samples per second per channel.

SourceCh The number of channels to be digitized and stored in the data file.

SourceChOffset, SourceChGain Calibration information defining conversion from AD units into physical units (µV). Raw data is converted into µV according to:

$$\text{calibrated}_{ch} = (\text{raw}_{ch} - \text{SourceChOffset}_{ch}) \times \text{SourceChGain}_{ch}$$

SourceMin, SourceMax For the source signal display, the minimum and maximum expected signal value in microvolts. SourceMin may exceed SourceMax to
allow inversion of the signal display.

SubjectName A textual ID for the subject. The subject name will appear in session directories and data file names.

SubjectSession A textual ID for the current session. Sessions correspond to data
directories. The path of a session directory is constructed according to:

{DataDirectory}/{SubjectName}{SubjectSession}

SubjectRun A number indicating the current run. Runs correspond to data files.
To avoid accidental loss of data, run numbers are automatically incremented from
the largest used value. Within a session directory, data file names are constructed
according to:

{SubjectName}S{SubjectSession}R{SubjectRun}

A data file's extension depends on the output file format (see Sect. 6.3.3).

VisualizeTiming Switches display of timing information on or off.

VisualizeSource Switches display of the raw source signal on or off.

VisualizeSourceDecimation An integer decimation factor for the source signal display. For example, if you specify a factor of 2, only every other sample is drawn in the source display. This option is very important for configurations with high
sampling rates, channel counts, and fast update rates, to ensure that BCI2000 can
process incoming blocks fast enough.

VisualizeSourceTime The amount of time displayed in the source signal display.

10.3.1.2 States

SourceTime A 16-bit time stamp with a resolution of 1 ms, and wrap-around oc-
curring every 65,536 ms. The time stamp is set immediately after a block of data
has been acquired from the A/D converter.

StimulusTime A 16-bit time stamp in the same format as the SourceTime state.
This time stamp is set immediately after the application module has updated the stimulus/feedback display.
Recording While data is being recorded this parameter is set to 1, 0 otherwise. In a data file, this state will always be 1.
Running 1 while data is being processed, 0 in suspended state. Setting this state to 0 from a filter, or over the App Connector interface (Sect. 6.4), will suspend BCI2000 operation.

10.3.2 AlignmentFilter

The AlignmentFilter performs temporal alignment of channel data. This is done using linear interpolation between subsequent time points.

Typically, the AlignmentFilter is used for A/D converters where channel sampling occurs subsequently rather than concurrently (e.g., in cases in which the device only has one sample-and-hold component). As a result, channels are time-shifted relative to each other by a considerable fraction of the sampling period. This time-shift must be corrected for to avoid adverse effects in certain filtering operations, such as spatial filtering.

Newer hardware, which is clocked at high speeds and employs oversampling to improve signal-to-noise ratio, may have no or only a negligible time-shift between channels.

10.3.2.1 Parameters

AlignChannels A nonzero value enables channel alignment.
SourceChTimeOffset A list of floating point values between 0 and 1. There must be one entry for each input channel. Each entry gives the amount of time-shift that is present for the respective channel, given in units of the sampling interval (i.e., [0, 1)). Alternatively, the list may be empty; then, an equidistant distribution of time shifts over the [0, 1) interval is assumed.

10.3.2.2 States

None.

10.3.2.3 Example

At a sampling rate of 250 Hz, the sampling interval is 1/(250 Hz) = 4 ms. If SourceChTimeOffset is an empty list, and if there are eight input channels, the
following time shifts are assumed:

C hannel								
Relative time shift	0	1/8	1/4	3/8	1/2	5/8	3/4	7/8
Absolute time shift	0	0.5 ms	1 ms	1.5 ms	2 ms	2.5 ms	3 ms	3.5 ms

Entering the values given in the relative time shift row into SourceChTimeOffset would have the same effect as providing an empty list.

10.3.3 TransmissionFilter

The TransmissionFilter forwards a subset of input channels to its output. Typically, it is used in the data acquisition module to select a subset of recorded channels for on-line processing (i.e., to select those channels that are being submitted to the Signal Processing module). This option is used to reduce data transmission overhead and processing load.

10.3.3.1 Parameters

TransmitChList A list of input channels to be forwarded to the filter's output. Channels may be specified by ordinal number, or textual label if available. Channel labels are forwarded if present for the input signal.

10.3.3.2 States

None.

10.3.4 SourceFilter

Many biosignal amplifiers offer filtering in hardware. Generally, they have a line noise hum filter, or "notch filter," built in, and perform some high pass filtering. For amplifiers that do not provide these filters themselves, the SourceFilter realizes filtering in software.

Unlike other signal processing filters, the SourceFilter filter will be applied immediately after data acquisition, and it will modify the data which will be saved to disk, i.e., it will behave just as if it were a hardware filter built into the amplifier.

All other signal processing filters are located in the Signal Processing module where they will be applied to the signal online but have no effect on the signal that is stored
in the data file.

10.3.4.1 Parameters

HighPassFilter Configures the high pass filter, which is realized as a first order infinite impulse response (IIR) filter:

- 0: disabled,
- 1: at 0.1 Hz.

NotchFilter Configures the notch filter, which is realized as a 2×3rd order Chebychev bandstop. The proper setting depends on your country:

- 0: disabled,
- 1: at 50 Hz (Europe, Asia, Africa, parts of South America)
- 2: at 60 Hz (North America, parts of South America).

10.3.4.2 States

None.

10.3.4.3 Remarks

Generally, the SourceFilter will be available in source modules connecting to amplifiers that require it. Adding the SourceFilter to modules that do not yet contain it requires recompilation.

To add the SourceFilter to a new or existing source module, add the following files to the project, and recompile:

- `BCI2000/src/shared/modules/signalsource/SourceFilter.cpp`
- `BCI2000/src/shared/modules/signalprocessing/IIRFilterBase.cpp`
- `BCI2000/src/extlib/math/FilterDesign.cpp`

10.3.5 BCI2000FileWriter

The BCI2000FileWriter component stores data in the native BCI2000 file format.

10.3.5.1 Parameters

SavePrmFile Specifies whether parameters are to be stored in a parameter file separate from the data file. The additional parameter file will be redundant, as native BCI2000 data files always contain the complete set of parameters.

StorageTime At the beginning of the recording, this parameter's content is overwritten with a string describing the current date and time. Any user-specified value is ignored.

10.3.5.2 States

None.

10.3.6 EDFFileWriter

The EDFFileWriter component stores data in the EDF File Format.

10.3.6.1 Parameters

EquipmentID A string that identifies the equipment provider.
LabID A string that identifies the recording laboratory.
SignalUnit A string specifying the physical unit of the calibrated signal. Unlike the notation used throughout the rest of BCI2000, this is usually “uV” rather than
“muV.”
SubjectSex An enumerated value specifying the subject’s sex:

- 0: not specified,
- 1: male,
- 2: female.

SubjectYearOfBirth Year the subject was born, in YYYY format.
TechnicianID A string that identifies the recording technician.
TransducerType A string that describes the transducer (sensor) type, e.g., “EEG:
Ag/AgCl.”

10.3.6.2 States

None.

10.3.7 GDFFileWriter

The GDFFileWriter component stores data in the GDF File Format.
In addition to the parameters provided by the EDFFileWriter, the GDFFileWriter provides an option to define mappings between state variables and GDF
events.

10.3.7.1 Parameters

SubjectYearOfBirth Year the subject was born, in YYYY format.
SubjectSex An enumerated value specifying the subject’s sex:

- 0: not specified,
- 1: male,
- 2: female.

TransducerType A string that describes the transducer (sensor) type, e.g., “EEG: Ag/AgCl.”

SignalUnit A string that specifies the physical unit of the calibrated signal. Unlike the notation used throughout the rest of BCI2000, this is usually “uV” rather than “muV.”

EquipmentID A string that identifies the equipment provider. Since GDF version 2.0, the equipment ID field has been 8-byte numeric rather than string-valued. Consequently, the EquipmentID parameter is treated as an integer value, and written into the numeric field. If the parameter string evaluates to 0 – e.g., because it begins with a letter rather than a digit – its first 8 bytes are copied into the numeric equipment ID field in a byte-wise manner. Remaining bytes are padded with zero bytes if the parameter’s string representation contains fewer than eight characters.

EventCodes BCI2000 does not prescribe the meaning of its state variables. GDF, on the other hand, associates a fixed set of events with certain numeric codes. Thus, a general mapping of BCI2000 states onto GDF events is not possible. Instead, GDF events are created via a user-defined set of mapping rules in the EventCode parameter, which also has a set of rules predefined for the most important cases.

The EventCodes parameter is a two-column matrix, with each row associating a boolean expression with a hexadecimal event code as defined in the GDF File Format. The expression is evaluated for each data block. Whenever its value switches from “false” to “true,” the GDF event code from the second column is entered into the GDF event table; whenever its value switches back from “true” to “false,” the same event code is entered into the table but with the most significant bit set to 1 (bitmask 0x8000).

The default value of the EventCodes parameter defines the most common mappings between BCI2000 states and GDF event codes:

Condition	Code	GDF event

TargetCode!=0	0x0300	trial begin
TargetCode==1	0x030c	cue up
TargetCode==2	0x0306	cue down
(ResultCode!=0)&&(TargetCode==ResultCode)	0x0381	hit
(ResultCode!=0)&&(TargetCode!=ResultCode)	0x0382	miss
Feedback!=0	0x030d	feedback onset

In addition to GDF events, BCI2000 state variables will be mapped to additional signal channels the same way as for EDF.

10.3.7.2 States

None.

10.3.8 NullFileWriter

The NullFileWriter component does not store brain signal data (null file format).
Individual filters may still write log files to the directory defined by the DataDirectory, SubjectName, and SubjectSession parameters.

10.3.8.1 Parameters

SavePrmFile Specifies whether there should be a parameter file created for each run.

10.3.8.2 States

None.

10.4 Logging Input Filters

BCI2000 provides several mechanisms for recording from different user interfaces (e.g., mouse position, key presses, and joystick position and buttons) at sample resolution. The input logger is the preferred method of storing this data, but several older methods are maintained for compatibility. The Input Logger is described first, followed by the obsolete methods.

10.4.1 Input Logger

BCI2000 allows you to record input from keyboard, mouse, and joystick at sample resolution. This information is recorded into state variables, and recording is enabled by specifying appropriate command line options when starting a source module.

Input from keyboard, mouse, or joystick will occur asynchronously with respect
to BCI2000's data processing. To account for this, input events are associated with
time stamps, stored in a BCI2000 event queue, and assigned sample positions once
data samples have been acquired.

When BCI2000 is distributed across multiple machines in a network, input devices must be attached to the machine that runs the data acquisition module.
This is because time stamps of data acquisition and input events must refer to a common physical time base to allow associating input events with sample positions.

In Microsoft Windows, keyboard, mouse and joystick devices attached via USB are limited to a polling rate of 125 Hz, which corresponds to a temporal resolution of 8 ms. When better timing resolution is required, you might consider recording into an additional analog channel, or using the amplifier's trigger input when available.

The input logger is enabled using command line parameters.

10.4.1.1 Parameters

LogKeyboard When set to 1 from the command line, this parameter enables recording of keyboard events into the KeyDown and KeyUp state variables. Enabled with `--LogKeyboard=1`

LogMouse When set to 1 from the command line, this parameter enables recording of mouse events. Enabled with `--LogMouse=1`

LogJoystick When set to 1 from the command line, this parameter enables recording of joystick state. Enabled with `--LogJoystick=1`

10.4.1.2 States

KeyDown, KeyUp Key events. When a key is pressed, "KeyDown" will be set to the key's virtual key code at the corresponding sample position. When a key is released, the key code will be written into the "KeyUp" state variable.

MouseKeys Mouse key state, with the left mouse button corresponding to bit 0, and the right mouse button corresponding to bit 1.

MousePosX, MousePosY Mouse position in screen pixel coordinates with an additional offset of 32,768, i.e., the main monitor's top left corner will be recorded as (32,768, 32,768).

JoystickXpos, JoystickYpos, JoystickZpos Position is recorded from Joystick #1. Each position state ranges from 0 to 32,767 with a resting position at 16,384.

JoystickButtons1, JoystickButtons2, JoystickButtons3, JoystickButtons4 Joystick button information. Each button state is either 1 when pressed or 0 when not pressed.

10.4.2 JoystickFilter (Obsolete)

In contrast to input loggers, regular filters are only updated once per sample block.
Thus, a filter that reads from an input device and stores the results in a state variable can detect changes in the input device only at a rate determined by the current

sample block size. Thus, for detecting asynchronous external events, input loggers are preferred. In any case, several filters for input/output functionality exist. They include the JoystickFilter.

The JoystickFilter records joystick movements into a state value, making it possible to use it for data analysis purposes.

Note: The JoystickFilter is superseded by BCI2000's input logging facility, and kept for compatibility with existing experiments. Make sure not to activate input logging in a configuration where the JoystickFilter is present as well; otherwise, corruption of logged data may occur.

10.4.2.1 Parameters

JoystickEnable Enables recording of joystick movements when nonzero.

10.4.2.2 States

JoystickXpos, JoystickYpos, JoystickZpos Each position state ranges from 0 to 32,767 with a resting position at 16,384.
JoystickButtons1, JoystickButtons2, JoystickButtons3, JoystickButtons4 Each button state is either 1 when pressed or 0 when not pressed.

10.4.3 KeyLogFilter (Obsolete)

The KeyLogFilter logs keyboard events (i.e., key presses) and the state of mouse buttons. These events are recorded in BCI2000 states. This allows for tracking of user responses. Temporal resolution is limited to the length of a sample block. A keypress at any time during a sample block interval will result in that key's code being recorded for all respective state values within this sample block.

Note: The KeyLogFilter is superseded by BCI2000's input logging facility, and kept for compatibility with existing experiments. Make sure not to activate input logging in a configuration where the KeyLogFilter is present as well; otherwise, corruption of logged data may occur.

10.4.3.1 Parameters

LogKeyPresses Enables or disables keypress logging. Independent of the value of
this parameter, the MouseKeys and PressedKey states will always be present in
the file if the KeyLogFilter was added to the module.

10.4.3.2 States

MouseKeys A 2-bit state with bit 0 representing left mouse button state.
PressedKey1, PressedKey2, PressedKey3 These states contain "virtual key codes" (as defined by the Win32 API) for up to three keys. When more than three keys are pressed simultaneously, only those are recorded that were pressed first. The association of keys with states depends on the order in which keys were pressed. A state value of zero indicates that no key was pressed.

10.4.4 MouseFilter (Obsolete)

The MouseFilter captures the mouse position on the screen in device coordinates.
Coordinates are always recorded.

Note: The MouseFilter is superseded by BCI2000's input logging facility, and kept for backward compatibility. Make sure not to activate input logging in a configuration where the MouseFilter is present as well; otherwise, corruption of logged data may occur.

10.4.4.1 Parameters

None.

10.4.4.2 States

MousePosX, MousePosY These states hold mouse cursor position in device coordinates, i.e., in units of screen pixels.

10.5 Signal Source Modules

10.5.1 SignalGeneratorADC

The SignalGeneratorADC filter generates a test signal suited for BCI purposes. The test signal is a sine wave overlayed with white noise and a DC component. Test signal amplitude may be controlled using the system's pointing device, which is

useful in testing sensorimotor-based BCI setups. The signal’s DC component may
be modulated by the value of a state variable, which is useful in testing ERP type
BCI setups.

10.5.1.1 Parameters

DCOffset An offset value common to all channels. May be positive or negative, and given in raw or calibrated units.

ModulateAmplitude Controls whether signal amplitude follows pointer (mouse, trackball, or similar) movement.

NoiseAmplitude White noise amplitude for all channels, given in raw or calibrated units. The noise itself is independent among channels.

OffsetMultiplier An arithmetic expression that evaluates to a multiplication factor applied to the DC offset as given by the DCOffset parameter. This makes it possible to create a test signal that depends on the value of state variables. For example, to create a simulated evoked response in the P300 Speller's copy spelling mode, enter StimulusType as the multiplier expression, and a nonzero value into the DCOffset parameter.

RandomSeed An initialization value for the system's random number generator. When a nonzero value is specified, the random number generator will always produce the same sequence, leading to identical pseudorandom noise, which is most useful for testing purposes. If this is zero, the random number generator will be initialized from system time, and thus lead to different noise each time.

SignalType Selects the output signal's numeric type. The following options are provided:

- 0: 16-bit signed integer (int16),
- 1: 32-bit IEEE floating point (float32),
- 2: 32-bit signed integer (int32).

SineAmplitude The test signal's maximum amplitude. Modulation will be linear in the range between zero and this maximum amplitude. A raw number refers to A/D units; when immediately followed with a voltage unit (such as µV, or mV), the number is interpreted according to the SourceChOffset and SourceChGain parameters.

SineChannelX Index of a channel that receives a test signal controlled by the pointer's (e.g., mouse's) horizontal position.

SineChannelY Index of a channel that receives a test signal controlled by the pointer's vertical position. If the index is zero, then the test signal is given on all channels.

SineChannelZ Index of a channel that receives a test signal controlled by mouse keys. For mouse key control, the pattern of pressed keys is translated into its corresponding 2-bit number. Signal amplitude is then proportional to this number.

SineFrequency Test signal frequency. When specified as a raw number, the frequency is given in terms of the sampling rate. Absolute frequencies may be given as decimal numbers or fractions when directly followed with Hz. Examples:

- 0.25 (half the Nyquist frequency),
- 10.5 Hz, or
- 20/3 Hz.

10.5.1.2 States

Any state may occur in the expression given in the OffsetMultiplier parameter.

10.5.2 gUSBampADC

The gUSBampADC filter acquires data from one or multiple g.USBamp amplifier/digitizer systems. g.USBamp is an amplifier/digitizer combination from g.tec medical engineering GmbH/Guger Technologies OEG (http://www.gtec.at).
Support for this device in BCI2000 consists of two components: A BCI2000-compatible Source Module (gUSBampSource.exe) and a command-line tool (USBampgetinfo.exe).

10.5.2.1 Hardware

The g.USBamp consists of 16 independent 24-bit A/D converters that can sample at up to 38.4 kHz per channel. Because there is one A/D converter for each channel, one particular sample is digitized at the exact same time for each channel. This is unlike with traditional A/D converter boards that only have one A/D converter.
BCI2000 has a feature that can align samples in time (parameter AlignChannels).
Because this feature is not needed in conjunction with the g.USBamp, it needs to be turned off (i.e., AlignChannels needs to be 0).

10.5.2.2 Parameters

AcquisitionMode If set to analog signal acquisition, the g.USBamp records analog signal voltages (default). If set to Calibration, the signal output is a sine wave test signal generated by the g.USBamp (which can be used to verify correct function/calibration). If set to Impedance, regular analog signal acquisition is preceded by an impedance test. This impedance test reports electrode impedances for each channel in kOhm. In impedance mode, the grounds and references are automatically connected in the amp internally (and the values of the parameters CommonGround and CommonReference are ignored). In this mode, you need to connect the ground and reference to block D.
CommonGround This parameter determines whether the g.USBamp internally

connects the GND inputs from all four blocks (A, B, C, and D) together. If enabled (default), then the signal ground only needs to be connected to one input
block, e.g., block A. Otherwise, all GND inputs need to be externally connected.

CommonReference The same as CommonGround, except for the signal reference.

DeviceIDs List of serial numbers (e.g., UA-2007.01.01) of all devices. If you have more than one device, this list determines the order of the channels in the recording and in the data file. If only one device is connected, this parameter may be set to auto.

DeviceIDMaster Serial number (e.g., UA-2007.01.01) of the master device that is generating the clock for all other (i.e., slave) amplifiers. If you only have one device, this parameter has to equal DeviceIDs or may be set to auto. If you have more than one device, then this parameter represents the serial number of the device whose SYNC goes to the slaves, i.e., the only device that has a cable connected at SYNC OUT, but none connected to SYNC IN.

DigitalInput Turn on digital input. If turned on, the last sampled channel on each amplifier will contain sampled values of digital input 0 on the DIGITAL I/O input block on the back of the device. For example, if SourceCh is 8, then channels 1–7 will represent analog inputs, and channel 8 will represent the digital input. Thus, if DigitalInput is turned on, SourceCh and SourceChDevices may be a maximum of 17. Future versions of this module will support more than one digital input.

DigitalOutput Turn on digital output. If turned on, the digital output channel 0 is set low for the duration of a data block's acquisition, and set high at the end. This is primarily used for the BCI2000 Certification process, but may also be employed for other purposes, such as synchronizing acquisition with an external device.

DigitalOutputEx If this parameter contains an arithmetic or boolean expression, digital output 1 will be set high whenever this expression evaluates to true (nonzero) and low when the expression evaluates to false (zero). An example for such an expression is: `( StimulusCode == 0 ) && Running )`. In this example, the digital output is high whenever no stimulus is presented and the system is running.

FilterEnabled Choose 1 if you want a band-pass filter, and 0 if you don't. Because the g.USBamp is a DC amplifier, its signals may have a substantial DC offset that you may want to filter prior to storage and processing.

FilterHighPass High-pass frequency for band-pass filter. You need to query the amp for possible values. See description of the USBampgetinfo tool (page 205) for more info.

FilterLowPass Low-pass frequency for band-pass filter. See description of the USBampgetinfo tool (page 205) for more info. Please note that, because the g.USBamp has a 6.8 kHz hardware-based antialiasing filter, internally samples at a

very high rate, and then downsamples the signal to the desired sampling rate, you
will never experience aliasing even if you do not enable a low-pass filter.

FilterModelOrder Model order for band pass filter. See description of the USBampgetinfo tool (page 205) for more info.

FilterType Type of band pass filter:

- 1=CHEBYSHEV
- 2=BUTTERWORTH

NotchEnabled The notch filter suppresses power line interference at 50 or 60 Hz. Choose 1 if you want a notch filter, and 0 if you don't.

NotchHighPass Similar to FilterHighPass.
NotchLowPass Similar to FilterLowPass.
NotchModelOrder Similar to FilterModelOrder.
NotchType Similar to FilterType.
SamplingRate The sampling rate of all connected g.USBamps. If you would like to use a bandpass or a notch filter, there needs to be a filter configuration for that particular sampling rate (see the section on the USBampgetinfo tool, page 205).
(g.tec Guger Technologies may be able to provide you with an updated driver configuration file if you need a different filter.)
The g.USBamp supports the following sampling rates: 32, 64, 128, 256, 512, 600, 1,200, 2,400, 4,800, 9,600, 19,200, and 38,400 Hz. All sampling rates are supported for one or more amplifiers. If you are sampling at high rates and from multiple amplifiers, the CPU may be overloaded depending on the speed of your computer and the BCI2000 configuration. In case you are experiencing problems (e.g., data loss, jerky display, etc.), increase the SampleBlockSize so that you are updating the system less frequently (usually, updating the system 20–30 times per second is sufficient for most applications), and increase Visualize → VisualizeSourceDecimation. This parameter will decrease the number of samples per second that are actually drawn in the Source display. For example, at 38,400 Hz, four amplifiers (64 channels), and a system update of 30 Hz, the computer would have to draw more than 73 million lines per second in the Source display! BCI2000 V3.0 also includes a new feature that automatically decimates the signal appropriately.
SignalType Defines the data type of the stored signal samples (int16 or float32). If the data type is int16, signal samples (which are produced by the amplifier in units of µV) are converted back into virtual A/D units (see Additional Information section below). If the data type is float32, the signals are stored in units of µV. In this case, SourceChOffset should be 0, and SourceChGain should be 1 (since the conversion factor from µV into µV is 1).
SourceChDevices The number of channels acquired from each device. If there is only one device, this parameter has to equal SourceCh. For example, ’16 8’ will acquire 16 channels from the first device listed under DeviceIDs, and 8 channels from the second device listed under DeviceIDs. Data acquisition always starts at channel 1. The sum of all channels (e.g., 24 in this example) has to equal the value of SourceCh.

SourceChList The list of channels that should be acquired from each device. The total number of channels listed should correspond to SourceCh. For more than one device, SourceChDevices determines how the SourceChList values are mapped to each device. For example if SourceChDevices = ’8 8’ and SourceChList = ’1 2 3 4 1 3 1 4 1 5 1 6 5 6 7 8 9 1 0 1 1 1 2 ’, then channels 1–4 and 13–16 will be acquired on the first device, and channels 5–12 will be acquired on the second device. These channels will be saved in the data file as 16 contiguous channels. The order of channels does not matter; i.e., ’ 1 2 3 4 ’ is the same as ’2 3 1 4’. The channels are always in ascending order on a single device. Channels may not be listed twice on a single device; e.g., entering ’ 1 2 3 4 5 6 7 1 ’ if SourceChDevices = ’8’ will result in an error. If this parameter is left blank (the default), then all channels are acquired on all devices.

10.5.2.3 States

None.

10.5.2.4 Additional Information

Unlike many other systems, the g.USBamp is a DC amplifier system that digitizes at 24 bit. Bandpass and notch filtering is performed on the digitized samples, resulting in floating point signal samples in units of µV. BCI2000 currently supports signed 16 bit integers, signed 32 bit integers and floating point numbers for its data storage.
If SignalType is set to int16 or int32, the floating point values acquired from the g.USBamp have to be converted back into integers before they can be stored and transmitted to Signal Processing. This is done by the following transformation:

$$\text{sample}_{\text{stored}}(\text{A/Dunits}) = \frac{\text{sample}_{\text{acquired}}(\mu\text{V})}{\text{SourceChGain}} \qquad (10.1)$$

In other words, when using the g.USBamp and storing data in 16/32 bit integers, it is important to select values for SourceChGain such that the resulting integers are in appropriate value ranges. This is particularly important for 16 bit integers that only have a limited resolution (0–65,535). Otherwise, signal clipping or loss of resolution will occur. In summary, unless storage or other considerations require the use of integer signals, we strongly recommend to store signals from the g.USBamp in floating point representation.

BCI2000 Signal Processing or any offline analysis routine can derive, as with any other BCI2000 source module, sample values in µV by subtracting, from each stored sample, SourceChOffset (i.e., zero), and multiplying it with SourceChGain for each channel. If SignalType is set to float32, data samples are stored in units of µV. In this case, SourceChGain should be a list of 1's (because the conversion factor between data samples into µV is 1.0 for each channel).

When values other than 0 and 1 are specified, a consistent data file will be produced, i.e., values will be transformed before they are written to the file, such that applying SourceChOffset and SourceChGain will reproduce the original values in µV.

10.5.3 gMOBIlabADC

The gMOBIlabADC acquires data from a g.MOBIlab device.Theg.MOBIlab is an amplifier/digitizer combination from g.tec medical engineering GmbH/Guger Technologies OEG (www.gtec.at).

10.5.3.1 Hardware

The g.MOBIlab device supports eight analog input channels digitized at 16 bit resolution and sampled at a fixed 256 Hz sampling rate. In its standard configuration, channels 1–2 have a sensitivity of ±100 µV, channels 3–4 have a sensitivity of ±500 µV, channels 5–6 have a sensitivity of ±5 mV, and channels 7–8 have a sensitivity of ±5V.

The input range of the A/D converter is approximately equal to this sensitivity. Thus, for example, one LSB for channel 1 or 2 is roughly $\frac{200\,\mu V}{65{,}536} = 0.003\,\mu V$. However, the actual input range of the A/D converter is slightly larger than the sensitivity of each channel (so that the A/D converter can detect when the amp saturates), and thus, exact LSB values have to be determined for each channel using a calibration signal.

This device has only one A/D converter. Thus, it digitizes signals from different channels at slightly different times. BCI2000 has a feature that can align samples in time (parameter AlignChannels, which needs to be enabled (i.e., AlignChannels needs to be 1)).

Additional features of the g.MOBIlab are two digital input/output lines. The g.MOBIlab source module is configured such that channel 9 corresponds to the value of the digital lines, which are configured as input lines.

10.5.3.2 Parameters

COMport Serial port of the attached g.MOBIlab device, e.g., `COM2:`
SamplingRate The sampling rate of the g.MOBIlab. This value has to be 256.
SourceCh The total number of channels. This number can be 1 to 9. If it is set to 9, then channels 1–8 represent eight analog input channels, and channel 9 represents the values of the two digital lines.

10.5.3.3 States

None.

10.5.4 gMOBIlabPlusADC

The gMOBIlabPlusADC acquires data from a g.MOBIlab+ device. The g.MOBIlab+ is an amplifier/digitizer combination from g.tec medical engineering GmbH/Guger Technologies OEG (http://www.gtec.at) which can transmit data
over a serial connection or wirelessly via a Bluetooth connection.

10.5.4.1 Hardware

The g.MOBIlab+ device supports eight analog input channels digitized at 16 bit resolution and sampled at a fixed 256 Hz sampling rate. Additionally, eight digital input lines can be sampled with the analog data, so that behavioral information (e.g., button presses) can be recorded as well. The amplifier has a sensitivity of ±500 µV. Thus, one LSB is roughly $\frac{1mV}{65,536} = 0.0153$ µV.

This device only has one A/D converter. Thus, it samples signals from different channels at slightly different times. BCI2000 has a feature that can align samples in time (parameter AlignChannels, which needs to be enabled (i.e., AlignChannels needs to be 1)).

Additional features of the g.MOBIlab+ are four digital input lines, and four digital input/output lines. The g.MOBIlab+ source module is configured such that channels 9–16 correspond to the value of the digital lines, which are configured as input lines. It is possible to configure one digital line in the output configuration, so that the line is pulsed during a data read. This is described further in the parameters section below.

If using Bluetooth, g.tec Bluetooth software must be installed prior to using the g.MOBIlab+. Please follow the instructions provided by g.tec.

10.5.4.2 Parameters

COMport Serial port of the attached g.MOBIlab+ device, e.g., COM7: This value is determined when the Bluetooth serial port is configured during installation.

SourceCh The total number of channels. This number can be 1 to 8, or 16. If it is set between 1 and 8, then channels 1–8 represent eight analog input channels. If it is set to 16, then channels 1–8 are analog, and channels 9–16 are digital inputs (see DigitalEnable).

SampleBlockSize Samples per digitized block. A value of 8 corresponds to a BCI2000 system update rate of 32 Hz.

SamplingRate The sampling rate of the g.MOBIlab+. This value has to be 256.

InfoMode Displays information about the g.MOBIlab+ device.

DigitalEnable If this is set to 1, then the eight digital lines are read as inputs. In this case, the total number of channels (SourceCh) must equal 16.

DigitalOutBlock If this is set to 1, then digital line 8 is set to output mode, and is set low at the onset of block acquisition, and set high after the block is read.
This allows the system timing to be measured, or to synchronize BCI2000 with an

external device.

10.5.4.3 States

None.

Fig. 10.10 Filters in the signal processing module

10.6 Signal Processing Filters

In the signal processing module, brain signals are processed by a series of filters that translate raw brain signals into device control signals. Thus, these filters realize feature extraction and translation. Feature extraction consists of filtering the signal spatially and temporally, which results in a set of extracted features. Signal translation consists of a linear classifier, which translates these features into control signals that differentiate amongst a small number of mental states (classes). Signal translation also includes the normalizer, which adjusts the classifier's output to zero mean and unit variance.

The sequence of these filtering procedures is shown in Fig. 10.10. The filters themselves are described in more detail below.

10.6.1 SpatialFilter

The SpatialFilter computes an instantaneous linear transformation of its input. Typically, the SpatialFilter's input is the unfiltered brain signal from the source module. The linear transformation that is applied by the spatial filter is described by a transformation matrix, and applied for each sample separately, i.e., not linking data across different points in time. This linear transformation can be parameterized in three different ways as described below.

Each spatial filter type uses a different algorithm to compute the linear transformation, and can therefore have implications on CPU load and performance. In the following, N denotes the filter's number of input channels, and M denotes its number of output channels. Typically, M is less than or equal to N.

10.6.1.1 Parameters

SpatialFilterType This parameter defines the method that will be used to implement the spatial filter. Choices are:

0: None No spatial filtering is performed; the input signal is copied to the output signal, and the spatial filter matrix is ignored.

1: Full Matrix The linear transformation applied to the input signal is defined by
the SpatialFilter matrix parameter. This is also the default, and matches behavior
in previous versions of BCI2000.
2: Sparse Matrix The sparse matrix filter uses the SpatialFilter matrix parame-
ter to define non-zero matrix entries. Each non-zero entry is given by an input
channel, output channel, and weight for that channel.
3: Common Average Reference (CAR) The common average reference spatial filter calculates the mean of all channels, and subtracts this value from the se-
lected output channels. This filter's output channels may be defined by the Spa-
tialFilterCAROutput parameter.

SpatialFilterCAROutput This parameter is a list of channels that define which channels should be output from the common average reference spatial filter, and
the order in which they should appear. That is, the location of the channel in this
list determines the output channel position. For example, if input channels `6, 7, 10, 12` should be passed to the output of the spatial filter as channels `3, 4, 1, 2`, then this parameter should be set to: `[10 12 6 7]`. Rather than numbers, channel names may be specified as defined in the ChannelNames parameter: e.g., `[C3 C4 CP3 CP4 Cz]`.

10.6.1.2 States

None.

10.6.1.3 Spatial Filter Remarks

Full Matrix
The full matrix filter uses the SpatialFilter parameter to define the linear transfor-
mation applied to the filter's input signal. In this matrix, columns represent input
channels, and rows represent output channels. Each matrix element defines a weight with which the respective input channel (column) enters into the respective output
channel (row).

If the spatial filter should realize an identity filter – not modifying its input – then
the SpatialFilter matrix should be set to a unit matrix (square matrix with ones on
the main diagonal, and zeros in all other elements).

In a typical EEG experiment with a fixed montage, you might want column labels to reflect the respective electrode location, simplifying the task of further modifications to the spatial filter. Also, specifying row labels to identify output channels allows you to use those labels in configuration of further stages of processing, such as the LinearClassifier.

Full matrix representation is the most general way to specify a spatial filter, and recommended for situations not allowed for by the remaining spatial filter types.

Compared to those, it is associated with a number of disadvantages:

- Complexity is O(NM). In situations with large sampling rates and/or a large number of channels, this may result in real-time problems due to high CPU load.
- Channel labels are not preserved across the filter. Due to the filter's general nature, no relation between input and output channel names can be inferred, and all output labels must be specified manually.
- The filter's specification depends on the order of input channels, which makes it interdependent with the TransmitChList parameter.

Sparse Matrix Filter Type

The sparse matrix filter uses the SpatialFilter parameter to define the relationship between input channels and output channels with a given weight. In this case, the SpatialFilter matrix must have three columns, and a row for each input/output relationship. The first column contains the input channel, and the third column defines the weight that the input channel is multiplied by before being assigned to the output channel, which is defined in the second column.

When specifying input channels in the first column, you may use channel names. In order to assign labels to output channels in sparse representation, use arbitrary labels in the (second) output channel column.

The sparse matrix method performance is determined completely by the number of elements (rows) in the SpatialFilter matrix. In the best case, a single channel is multiplied by the weight and assigned to the specified output channel; this would take far less CPU time than the CAR method, and possibly the "none" option as well.

In a realistic scenario, all N input channels will be used to calculate $M \leq N$ output channels; thus, complexity is between O(N) and O(NM), with $O(N^2)$ in the worst case.

Sparse matrix worst-case performance will be close to that of an $N \times N$ "full" spatial filter matrix. Thus, for spatial filter configurations that depend on electrode/sensor locations such as Laplacian filtering, filter definition in terms of a sparse matrix using channel labels appears most advantageous.

Common-Average Reference

It is important to note that all channels passed to the spatial filter (typically defined in the TransmitChList parameter) are used in the CAR calculation, but only a subset of these channels are actually output and passed to the next step in the signal

processing chain. If this parameter is left blank, then all input channels are passed to the output, and the number of input channels equals the number of output channels.

The common-average reference has a complexity of O(N + M), providing the next best performance in most circumstances. It is possible to create a CAR using either the full-matrix or sparse matrix options; however, the CAR method only calculates the mean value once per sample, and subtracts it only from the selected output channels. In order to implement a CAR in a full-matrix, the mean must be recalculated for every output channel, which is not as efficient, particularly for high channel count systems.

10.6.2 ARFilter

The ARFilter computes an autoregressive model of its input (i.e., spatially filtered brain signals in an unmodified BCI2000 system) using the Maximum Entropy Method (Burg algorithm). Spectral estimation is done separately for each of the filter's input channels. Its output may be raw AR coefficients, or an estimated power or amplitude spectrum collected into bins. Thus, it can be used in place of the FFTFilter, which also computes a power spectrum.

10.6.2.1 Parameters

For all frequency-valued parameters, float values without any unit are interpreted as fractions of the sampling rate; absolute frequencies may be given when followed with Hz, as in the following examples:

- 0.5 refers to the Nyquist frequency (half the sampling rate).
- 10.3 Hz specifies a value of 10.3 Hz, regardless of the sampling rate.
- 15/2 Hz specifies a value of 7.5 Hz.
- The unit must immediately follow the number.

BinWidth A single non-negative float value that represents the width of a single bin, e.g., "3 Hz."

Detrend Determines whether signal samples are detrended prior to spectral estimation. Possible values are

- 0: no detrending,
- 1: mean removal,
- 2: linear trend removal.

EvaluationsPerBin A single non-negative integer value that represents the number of uniformly spaced evaluation points that enter into a single bin's value.

FirstBinCenter A float value representing the center of the first frequency bin, e.g., "5 Hz."

LastBinCenter A float value representing the center of the last frequency bin.

ModelOrder The order of the autoregressive model. This value approximately corresponds to the maximum number of peaks in the resulting spectrum.

OutputType Possible values are:

- 0: spectral amplitude,
- 1: spectral power,
- 2: AR coefficients.

If the output is a spectrum, the output signal's elements correspond to uniformly spaced frequency bins. For raw AR coefficients, the first output signal element contains total signal power, followed by the model's denominator coefficients.

WindowLength The length of the input data window over which the model/

spectrum is computed, given as a time value in seconds (then immediately fol-
lowed by the unit), or the number of signal blocks (e.g., `1.34s`, `500ms`, or `5`).

10.6.2.2 States

None.

10.6.2.3 ARFilter Remarks

AR coefficients are actually the coefficients of an all-pole linear filter that is fitted to reproduce the signal's spectrum when applied to white noise. Thus, the estimated power spectrum directly corresponds to that filter's transfer function, divided by the signal's total power. To obtain spectral power for finite-sized frequency bins, that power spectrum needs to be multiplied by total signal power, and integrated over the frequency ranges corresponding to individual bins. This is done by numerical integration, evaluating the spectrum at evenly spaced evaluation points, summing, and multiplying by bin width to obtain the power corresponding to a certain bin. For amplitude rather than power spectrum output, bin integrals are replaced with their square roots.

10.6.2.4 Example

For a typical EEG application, you might use the following configuration:

```
ModelOrder= 16
FirstBinCenter= 0Hz
LastBinCenter= 30Hz
BinWidth= 3Hz
EvaluationsPerBin= 15
```

This will result in 11 bins, with the first bin covering the DC range from −1.5 to 1.5 Hz. Due to symmetry of the transfer function, this is twice the integral from 0 to 1.5 Hz. The last bin will cover the range from 28.5 Hz to 31.5 Hz. Evaluation points within each bin are 0.2 Hz apart.

10.6.3 FFTFilter

The FFTFilter applies a short-term Fast-Fourier Transformation (FFT) to selected channels of its input signal, resulting in a time series of frequency spectra. The com-
puted spectra may be displayed in visualization windows. Typically, the FFTFilter is used for spectral estimation and demodulation, instead of the ARFilter.

10.6.3.1 Parameters

FFTInputChannels A list of input channels for which the FFT is computed. When FFTOutputSignal is set to a value other than 0, FFTInputChannels list entries determine the correspondence between input and output channels.

FFTOutputSignal Depending on configuration, the FFTFilter's output signal will be the computed spectrum, or the unchanged input. Possible values are

0: input connect-through This option allows using the FFTFilter for visualization purposes.
1: power spectrum As with the ARFilter, the output signal's elements will correspond to frequency bins.
2: complex amplitudes The output will be complex Fourier coefficients in half-complex format, with the spectrum's imaginary part appended to the real part.

FFTWindowLength The length of the input data window over which the FFT is computed, given as a time value in seconds (then immediately followed by the
unit), or the number of signal blocks (e.g., `1.34s`, `500ms`, o r`5`). The FFT will be computed once per data block. If the length of the input data window exceeds
that of a data block, FFT windows will overlap. If the data window is shorter than
a data block, only the most recent samples will enter into the FFT.

FFTWindow Selects the type of side-lobe suppression window. Possible values are

1 Hamming window,
2 Hann window,
3 Blackman window.

VisualizeFFT A nonzero value selects visualization of the FFT-computed power spectrum. Independently of the FFTOutputSignal parameter's value, it is always
the power spectrum that is visualized.

10.6.3.2 States

None.

10.6.3.3 FFTFilter Remarks

The FFTFilter requires the FFTW3 library which, for licensing reasons, you need to obtain separately from BCI2000. The FFTFilter uses the FFTW3 library to do the actual FFT computation, which is released under the GNU pub-
lic license (GPL). Please download the windows version of FFTW 3.01 from http://www.fftw.org/install/windows.html.

In order to make the FFTW library available to BCI2000, put `FFTW3.DLL` into your BCI2000 installation's prog directory. When using the command line ver-
sion of the FFTFilter, put a copy of `FFTW3.DLL` into your BCI2000 installation's

`tools/cmdline` directory.

For recent Windows builds of FFTW3, the naming scheme has changed. If you would like to use such a build with BCI2000, put a copy of the file `libfftw3-3.dll` into `BCI2000/prog` and rename it to `FFTW3.DLL`. This is currently untested.

10.6.4 P3TemporalFilter

The P3TemporalFilter is often used instead of the ARFilter or FFTFilter. It performs buffering and averaging of epochs of data as required for online classification of evoked responses (ERPs). It averages over epochs of data that are recorded in response to a number of stimuli; averaging is done separately for each stimulus.
When a fixed number of epochs have been accumulated for a given stimulus, the P3TemporalFilter computes their temporal average, and reports the average wave form(s) in its output signal. Whenever a temporal average is reported, the StimulusCodeRes state is set to the stimulus code that the average is in response to.

Typically, the P3TemporalFilter's output is sent into the LinearClassifier which takes waveform data from multiple locations and time points to linearly combine them into a single output. This number can represent the size of the evoked response for each stimulus. Application modules such as the StimulusPresentation and P3Speller can then provide feedback on this output.

10.6.4.1 Parameters

EpochLength Determines the duration of an epoch. An epoch begins with the onset of its associated stimulus. Epoch length may be specified in blocks as a raw number, or in seconds when immediately followed with a unit: e.g., `500ms`.

EpochsToAverage Determines the number of epochs that will be accumulated before reporting their average.

TargetERPChannel For waveform visualization, selects the channel to present in the average waveform display. Channels may be given by ordinal number, or textual label.

VisualizeP3TemporalFiltering If nonzero, average waveforms will be presented graphically to the investigator.

10.6.4.2 States

StimulusCodeRes When reporting a waveform average, this state contains the associated stimulus code. A StimulusCodeRes value of 0 indicates that the

P3TemporalFilter's output does not contain a valid waveform average, and should be ignored by the application module.

StimulusTypeRes When reporting a waveform average, this state is 1 if the associated stimulus was marked as "attended" on presentation, and 0 if the stimulus was not marked as "attended." In other words, the value of StimulusTypeRes at the time of waveform reporting matches that of StimulusType at the time of stimulus presentation.

10.6.4.3 States Used for Input

StimulusBegin (optional) When this state is present, it is assumed that a nonzero value indicates stimulus onset. When there is no StimulusBegin state present, stimulus onset will be derived from the StimulusCode state.

StimulusCode The code of a stimulus being presented. When there is no StimulusBegin state present, a switch of StimulusCode from zero to a nonzero value indicates stimulus onset. For averaging, epochs are grouped according to this state's value at stimulus onset.

StimulusType This state indicates whether a stimulus is marked as attended. I ts value is stored along with a stimulus presentation's associated wave forms.

10.6.5 LinearClassifier

The ARFilter, FFTFilter, or P3TemporalFilter (or any other filter you may have written) extract signal features from spatially filtered brain signals. The LinearClassifier subsequently translates these features into output control signals using a linear equation. Thus, each control signal is a linear combination of signal features. Input data has two indices (N channels × M elements), and output data has a single index (C channels × 1 element); thus, the linear classifier acts as a N × M × C matrix, determining the output after summation over channels and elements:

$$\text{output}_k = \sum_{i=1}^{N} \sum_{j=1}^{M} \text{input}_{ij} \, \text{Classifier}_{ijk} \qquad (10.2)$$

In a BCI based on periodic brain signal components (such as a mu rhythm-based BCI), the LinearClassifier's input is the time-varying amplitude or power spectrum for a number of spatially filtered EEG channels. Its output is normalized with respect to mean and variance, and then used as a control signal to determine cursor movement.

In an ERP-based BCI (such as the P300 BCI), the LinearClassifier's input is a sequence of averaged EEG time courses obtained in response to a number of stimuli, and its output is considered to represent the likelihood for each of these responses to be the desired evoked response.

10.6.5.1 Parameters

Classifier The Classifier parameter is a sparse matrix definition in which each row

corresponds to a single matrix entry. Columns correspond to

1. input channel,
2. input element (bin in the spectral case, time offset in the ERP case),
3. output channel,
4. weight (value of the matrix entry).

Input channels may be specified by ordinal number, or by textual label if available
(e.g., CP4). Input elements may be given as ordinal number, or using appropriate
units (e.g., 10Hz,or120ms).

10.6.5.2 States

None.

10.6.5.3 Mu Rhythm Classification Examples

For these examples, let us assume that you set the ARFilter's FirstBinCenter to 0, and BinWidth to 3Hz. This allows you to refer to the respective bins by their frequency, i.e., 12Hz rather than 5. We also assume that, in the SpatialFilter, you
have entered labels for output channels. This allows you to refer to channels by
their names, i.e., CP3 rather than 7.

1D Cursor Movement
In this example, you want to give feedback from electrode CP4, using the amplitude
between 10.5Hz and 13.5Hz for cursor feedback. Then, the Classifier parameter will have a single row that contains

Input channel	Input element	Output channel	Weight
CP4	12 Hz	1	1

2D Cursor Movement
In this example, you want to use mean activity from the left and right hand areas
at 12Hz to control movement in horizontal direction. Additionally, you want the
difference between left and right hand areas at 24Hz to control movement in vertical
direction. In the CursorTask application, the horizontal direction (X) corresponds to channel 1, and the vertical direction corresponds to channel 2. Accordingly, your Classifier parameter will have the following four rows:

Input channel	Input element	Output channel	Weight
CP3	12 Hz	1	0.5
CP4	12 Hz	1	0.5

CP3	24 Hz	2	−0.5
CP4	24 Hz	2	0.5

Note that, in the above example, subtracting CP3 from CP4 in the classifier is
not equivalent to taking the difference in the SpatialFilter. This is because (at least for a mu rhythm-based BCI) spatial filtering is followed by computation of spectral
amplitudes, and feature combination amounts to an addition of spectral amplitudes.
Computing spectral amplitudes involves taking the absolute value (or its square),
which is a nonlinear operation, where typically $|A - B| = |A| - |B|$.

10.6.5.4 ERP Classification Example

Often, you will use a computer program to optimize the classifier for use with ERPs (such as P300 GUI or P300 Classifier). However, for the sake of an instructive example, let us assume that you want to classify based on the temporal mean between 280 and 300ms and the spatial mean from electrodes Cz and Pz, and that
your sampling rate is 250Hz. Then, there will be six samples in that range, starting with sample number 70:

Input channel	Input element	Output channel	Weight
Cz	70	1	1
Cz	71	1	1
Cz	72	1	1
Cz	73	1	1
Cz	74	1	1
Cz	75	1	1
Pz	70	1	1
Pz	71	1	1
Pz	72	1	1
Pz	73	1	1
Pz	74	1	1
Pz	75	1	1

Note that, unlike in the case of spectral features, there is no difference between
spatially combining channels in the LinearClassifier or in the SpatialFilter. Thus, you might as well combine Cz and Pz into a channel labeled Cz+Pz in the SpatialFilter, and then use this classifier configuration:

Input channel	Input element	Output channel	Weight
Cz+Pz	70	1	1
Cz+Pz	71	1	1
Cz+Pz	72	1	1
Cz+Pz	73	1	1
Cz+Pz	74	1	1
Cz+Pz	75	1	1

10.6.6 Normalizer

The Normalizer applies a linear transformation to its input signal, i.e., the control signals produced by the classifier, so that the output control signal is in a certain value range. For each channel (index denoted with i), the normalizer subtracts an offset and multiplies the result with a gain value. As described later, these offset and gain values can either be manually defined or can be determined automatically during online BCI2000 operation using an adaptation procedure:

$$\text{output}_i = (\text{input}_i - \text{NormalizerOffset}_i) \times \text{NormalizerGain}_i \qquad (10.3)$$

If enabled, the Normalizer estimates offset and gain values adaptively from the past statistics of its input in an attempt to make its output signal zero mean and unit variance. The Normalizer uses “data buffers” to accumulate its past input according to user-defined rules. These rules are called “buffer conditions,” because they are given in terms of boolean expressions. Each data buffer is associated with such a boolean expression. Whenever an expression evaluates to “true,” the current input will be appended to the associated buffer. Whenever it comes to updating offset and gain values, the Normalizer will use the content of its buffers to estimate data mean and variance. The offset will then be set to the data mean, and the gain to the inverse square root of the data variance, i.e., the inverse of the data standard deviation.

10.6.6.1 Parameters

For each channel of the Normalizer’s input signal, adaptation is treated independently. Offsets, gains, and choice of adaptation are represented as list parameters, where each entry in the list corresponds to a signal channel. Buffer configuration is done in matrix form, where columns correspond to signal channels and rows correspond to adaptation buffers.

Adaptation A list of values that determines adaptation strategy individually for

each input channel (i.e., control signal). Possible values are

- 0 for no adaptation,
- 1 for adjusting offsets to zero mean,
- 2 for adjusting offsets to zero mean and gains to unit variance.

BufferConditions A matrix that consists of boolean expressions. Expressions may involve state variables and the components of the Normalizer's input signal (see examples below). Each matrix entry represents a data buffer that is a ring buffer of length BufferLength. Whenever a buffer's expression evaluates to `true`, the current value of the input signal will be put into the buffer (overwriting its oldest data once the buffer is filled). Columns correspond to control signal channels. Buffers in a certain column will buffer data from the corresponding signal channel, and will be used in adaptation of that channel only. Within columns, the order

of buffers does not affect computation. Empty expressions do not have any effect on the computation. Thus, it is possible to have a different number of buffers for different channels. As an example, a buffer to store data for the first target in the Cursor Task and during feedback only, should have an expression such as `(Feedback)&&(TargetCode==1)`.

BufferLength The maximum length of each data buffer. The length is specified in data blocks if given as a raw number, and in seconds if given as a number followed by the character `s`. All data buffers have the same capacity. Once a data buffer is filled, its older entries will be replaced with new data (ring buffer). In previous versions of BCI2000, buffer lengths were specified in terms of "past trials." This enforced the notion of a "trial," and did not generalize to continuous adaptation.

NormalizerOffsets, NormalizerGains Lists of offset and gain values where each entry corresponds to one control signal channel. These values will be updated depending on the channel's adaptation configuration in the Adaptation parameter.

Update Trigger A boolean expression that triggers adaptation when changing to `true` from `false`. Generally, continuous adaptation within trials is not desired. Usually, adaptation will be set to occur at the end of a trial. This is achieved with UpdateTrigger expressions such as `Feedback==0` or `TargetCode==0`. For continuous adaptation, specify an empty string in the UpdateTrigger parameter.

10.6.6.2 States

Buffer condition expressions and the UpdateTrigger expression may involve any states present in the system. Expressions are checked for syntactical correctness and whether the states that are referred to in these expressions are also present in the system.

Adaptation Rationale

It may appear crude to use the total data variance for the adaptation – why not use linear regression on data labels (target codes) to separate user controlled (task determined) from noise variance? User controlled variance would then correspond to target separation on the feedback screen, which is what we want to normalize in

the first place.

However, a closer look reveals that the “relative size” of user controlled variance,

and noise variance is crucial. When that “signal” variance is small compared to noise variance, we would be ill advised to use it in normalization – this would only lead to enlarged noise, and an erratically moving cursor on the feedback screen. In this case, we rather want to normalize by noise variance, to keep the cursor well-behaved. At

the same time, total variance approaches noise variance in this limit because signal

variance is small.

On the other end of the spectrum, we have a signal variance that is large com-

pared to noise variance. Here, we clearly want normalization by signal variance.

However, the total variance will be dominated by signal variance. Thus, in the limit of high signal-to-noise ratio, total variance again is the quantity by which we want

to normalize. Thus, no matter whether signal-to-noise ratio is high or low, total data variance appears to be a good choice for normalization.

Finally, it would also be possible to adaptively estimate the signal dynamics of the signal features (such as spectral amplitudes), rather than simply adapting the classifier output, i.e., control signal values. While this seems appealing mathematically and has been shown to produce valuable results [7, 8], it also requires estimation of a potentially large number of features. This implies that the resulting system will generally be less stable, that adaptation will take much longer, and that appropriate function of such an adaptation scheme will require careful configuration by an expert. Consequently, we chose the procedure described above for signal adaptation within BCI2000.

Typical Use

The Normalizer's input is the output of the Classifier.TheNormalizer transforms this input into a control signal with zero mean and unit variance. This control signal is then transmitted to an application module. Because the application module can assume that each control signal has zero mean and unit variance, it can easily relate these control signals to task-specific parameters such as window size, screen update rate, cursor velocity, and trial duration.

10.6.6.3 Examples

Trial-Based 1D Feedback Task with Three Targets

In this example, only data from the feedback phase should enter into the adaptation. To make sure that targets contribute equally to the adaptation, we use a single buffer for each target. We use a 3-rows-by-1-column BufferConditions matrix (see below). Depending on which control signal should be adapted on, all of these conditions need to be entered in the first, second, or third column of the matrix (corresponding to x, y, and z direction when used with the CursorTask application module, respectively).

```
(Feedback)&&(TargetCode==1)
(Feedback)&&(TargetCode==2)
(Feedback)&&(TargetCode==3)
```

We want to use data from approximately three previous trials of each target. The feedback duration (i.e., the duration of cursor movement) is 2 seconds. Thus, we set

the buffer length to the equivalent of three feedback durations:

```
BufferLength= 6s
```

Adaptation should happen at the end of each trial, when feedback is finished.

Thus, we set UpdateTrigger to an expression that changes to “true” when feedback
ends:

```
UpdateTrigger= (Feedback==0)
```

To achieve continuous movement in, say, the x direction, we need a constant normalizer output on that channel. To be consistent with the task module's FeedbackDuration parameter, this output should be constant at +2 in order for the cursor to cross the entire screen during a trial, and +1 when cursor movement begins at the screen's center. This corresponds to the following settings for the channel in question: Adaptation = 0, NormalizerOffset = − 1, NormalizerGain = 1 o r 2 , respectively.

Trial-Based 2D Feedback Task with Four Targets
Leaving everything else as in the previous example, we now have two dimensions corresponding to left-right (channel 1) and up-down (channel 2). The target positions are as indicated below:

```
-----------------------------
|           ##1##            |
|#                          #|
|2                          3|
|#                          #|
|           ##4##            |
-----------------------------
```

We use data from targets 1 and 4 to adjust channel 2, and targets 2 and 3 to adjust channel 1. Accordingly, the BufferConditions matrix is

```
(Feedback)&&(TargetCode==2) (Feedback)&&(TargetCode==1)
(Feedback)&&(TargetCode==3) (Feedback)&&(TargetCode==4)
```

Continuous 1D Control Without Pre-defined Targets
For this example, we assume that, over a period of 10 minutes, all output values will occur with approximately equal frequency, or at least have a symmetric distribution around zero. The difference from the previous examples is that we here do not assume any knowledge about position and timing of targets. This example could realize operation of BCI2000 with the Dasher spelling system, or with other devices that expect statistically balanced input. The BufferConditions matrix will have a single entry containing a constant expression:

1

This way, data will always be buffered. There are no trials. We want a continuous
adaptation to the values of the last 10 minutes. Thus, we set the BufferLength
parameter to `600s`,or`(10*60)s`. For continuous adaptation, we enter an “empty string” (not a constant 0 expression) for UpdateTrigger.

10.7 Additional Signal Processing Filters

10.7.1 LPFilter

The LPFilter is a simple single-pole temporal low-pass filter with a time constant T (given in units of a sample's duration), a sequence $S_{in,t}$ as input and a sequence
$S_{out,t}$ as output (where t is a sample index proportional to time), where

$-1/T$

−1/T −1/T

Typically, the LPFilter is used to remove high-frequency noise from the Classifier's output, i.e., to smooth the resulting control signals.

10.7.1.1 Parameters

LPTimeConstant The filter's time constant in units of sample blocks, or in seconds if followed with an s. Consistent with its mathematical limit, a value of LPTimeConstant= 0 disables the LPFilter.

10.7.1.2 States

None.

10.7.2 ConditionalIntegrator

The ConditionalIntegrator filter accumulates (integrates) its input signal over time, depending on the value of a given boolean expression. Typically, the ConditionalIntegrator is used in off-line analysis of data collected in a cursor movement paradigm. During on-line operation, the feedback cursor's position represents the integral of the control signal. For off-line parameter simulation experiments, the ConditionalIntegrator performs this integration, resulting in an output equivalent to cursor position on the feedback screen. A typical feedback task sets the Feedback state to 1 during cursor movement. Accordingly, one would use IntegrationCondition= Feedback in an off-line simulation.

10.7.2.1 Parameters

IntegrationCondition A boolean expression that determines whether the signal is integrated. When the expression first evaluates to true, the filter's output is set to

zero. Then, while the expression evaluates to true, filter input is integrated, and the integral's current value is returned as the filter output. When the expression first evaluates to false, filter output will be kept at the last integration value, and will stay there until the expression again evaluates to `true`.

10.7.2.2 States

Any existing state may be part of the IntegrationCondition expression.

10.7.3 StateTransform

The StateTransform filter replaces state values with values of an arithmetic expression. Typically, the StateTransform filter is used as a functional equivalent for cursor hit detection in off-line data analysis, using the output of the ConditionalIntegrator filter to determine cursor position. When the cursor hits a target, a typical cursor movement task sets the ResultCode state to the number of the target that was hit. For the case of 1D feedback with two targets, and when the filter's input is the integrated control signal as output by the ConditionalIntegrator, the following StateTransforms matrix achieves this behavior:

State	Expression
ResultCode	(ResultCode > 0) ∗ (1 + (Signal(1,1) > 0))

10.7.3.1 Parameters

StateTransforms Any number of transforms, specified in the form of an (N × 2) matrix. Each row corresponds to a transform. Within a row, the first column gives the name of the state to be transformed, and the second column gives the expression that replaces that state's value. The expression may also involve the value of the state it replaces.

10.7.3.2 States

Any state may be replaced, and any state may occur in the replacement expression.

10.7.4 ExpressionFilter

The ExpressionFilter uses arithmetic expressions to determine its output signal. As arithmetic expressions may contain state variables and the filter's input signal, this provides a powerful way to modify data processing according to BCI2000 system state, to introduce state variable information into additional signal channels, or to replace processing results with system state information.

10.7.4.1 Parameters

Expressions A matrix of strings that represent arithmetic expressions. These expressions determine the filter's output signal. Output signal dimensions are derived from matrix dimensions:

- matrix rows correspond to signal channels, and
- matrix columns correspond to signal elements (samples).

For each signal block, each of the expressions is evaluated, and the result is entered into the corresponding element in the output signal. Expressions may contain references to the filter's input signal, and to state variables (see examples below).
When the Expressions parameter is an empty matrix, the ExpressionFilter will simply copy its input into its output.

10.7.4.2 States

Any available state may enter into one of the expressions.

10.7.4.3 Examples

The following 2-by-2 matrix will replace a 2-by-2 input signal with its square. Additionally, inserting `*(ResultCode==0)` into each entry will change the output to zero when the ResultCode state variable is nonzero.

```
Signal(1,1)^2 Signal(1,2)^2
Signal(2,1)^2 Signal(2,2)^2
```

When the Input Logger is used to track a joystick position, the JoystickXpos and JoystickYpos state variables represent joystick position. When the ExpressionFilter is present in the signal processing module, placed between LinearClassifier and Normalizer, it may be configured to control the cursor directly by joystick position,

using this 2-by-1 matrix:

```
JoystickXpos
JoystickYpos
```

In the same configuration, to re-enable cursor movement by the output of signal pro-
cessing without removing the ExpressionFilter from the signal processing module, either set the Expressions parameter to an empty matrix, or use this matrix:

```
Signal(1,1)
Signal(2,1)
```

10.7.5 MatlabFilter

The Matlab filter allows you to implement the algorithms of your choice in Matlab. Once BCI2000 is running with the Matlab filter, you will see that a Matlab command line window has opened. In that command line window you can type commands
that show you the variables that BCI2000 communicates to the Matlab engine. For
example, you may enter one of the following commands:

```
% show the variables
whos

% plot the first channel of the data (see below)
plot(bci_InSignal(1,:))

% plot the first channel of the data and continuously
% update the plot (see below)
while(1); plot(bci_InSignal(1,:)); pause(0.01); end
```

If you try these examples above like this, you will notice that Matlab takes quite a
considerable amount of time to open a new figure. While the figure is being opened by Matlab, the engine is blocked, which causes the MatlabFilter to fail writing new
data to the engine. Hence the MatlabFilter will return an error and you will have to
restart BCI2000. The reason is that the Matlab engine gives you access through the
command window, but the Matlab engine is not capable of executing the commands that it receives from BCI2000 and the commands that it receives from you through
the command window simultaneously.

To get the above example to run correctly, you will have to open the figure prior
to starting BCI2000 by typing figure (this will open an empty figure). Subsequently, once BCI2000 is running, the content of the figure can be updated.

However, the above example already shows that the Matlab engine is not intended to be used concurrently with the BCI2000 MatlabFilter and from the command window. Instead of typing your own commands in the command window, you will have to give full control of command execution to the MatlabFilter to ensure that timing

is controlled. The way that BCI2000 and Matlab interact is that each of the components of a standard filter is mapped onto a corresponding Matlab function. If the Matlab filter is running within BCI2000, it will call the Matlab engine and execute the required Matlab function. The easiest way of getting started with the Matlab filter is by using the tutorials on IIR bandpass filtering followed with RMS envelope computation and linear classification in Sect. 7.4.

10.7.5.1 Parameters

The Matlab filter does not have a set of default parameters that it uses. Instead, the user-supplied Matlab functions that are executed by the Matlab filter specify the parameters. After initialization, these parameters are displayed in the Operator and can be modified there.

10.7.5.2 States

None.

10.7.5.3 Troubleshooting

Matlab doesn't find your functions Make sure to either set Matlab's working directory to the directory that contains your functions, using the `--MatlabWD=<path>` command line option, or add the respective directory to your Matlab path. We generally recommend the first option.

There is no Matlab engine started up Execute `matlab/regserver` from the command line when logged in with administrative privileges.

10.8 Application Modules

10.8.1 Cursor Task

The purpose of the Cursor Task is to provide a BCI2000 user application module that can realize 1D, 2D, or 3D cursor movement tasks. It displays a box-shaped scene in which a ball-shaped cursor moves and is controlled by the output of the

Signal Processing Module. In this scene, targets appear as cuboids or rectangles.
The box, cursor, and targets may be texturized.

The Cursor Task implements a cursor movement task based on a three-dimensional control signal communicated to it by a BCI2000 Signal Processing module. This task progresses through five subsequent stages. These stages are illustrated in the timeline shown in Fig. 10.11. In stage 1, the screen shows an empty

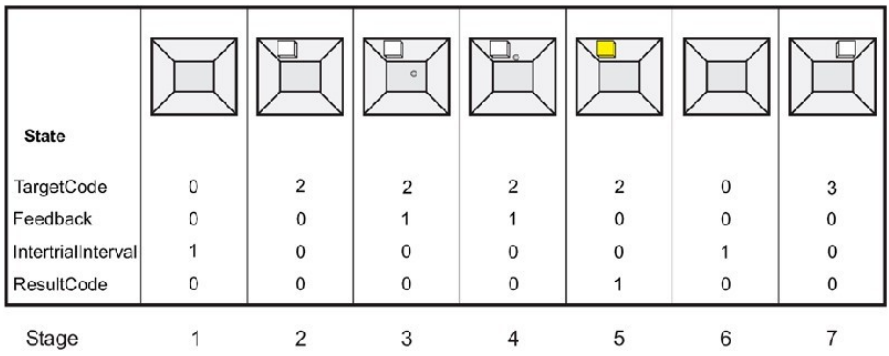

Fig. 10.11 Timeline for the Cursor Task

workspace. This period is called Inter-Trial Interval. Subsequently, a target (that is represented as a cuboid) appears in one out of n possible locations. This period is called Pre-Trial Pause. After the pre-trial pause, the cursor appears in stage 3. It immediately starts to move as determined by the 3-dimensional control signal. During stages 3 and 4, the user's task is to move the cursor towards and into the target. This period of cursor movement is called the Feedback Period or Trial Period. Period 4 can end in one of three ways: Either the cursor hits the correct target, it misses by hitting any other of the defined targets, or the feedback period takes too long and times out. Stage 5, the Reward Period, follows stage 4. The cursor disappears and the target changes its color to indicate completion of the trial period. After a defined duration, the target disappears and the next trial starts with an Inter-Trial Interval.

Visual Representation

The visual representation of the Cursor Task consists of a three-dimensional workspace (see Fig. 10.12) that can (if selected) be indicated by five bounding rectangles. These rectangles can have a user-selectable texture, which is the same for each rectangle. Targets are represented by cuboids, whose edges can also have a particular texture. Finally, the cursor is represented by a sphere. It, too, may have a user-defined texture. To facilitate depth perception, the cursor's color provides an additional cue about the cursor's Z position as follows. The operator specifies the

cursor’s color at the top-most and at the bottom-most Z positions. For any position
between these extremes, the cursor’s color will be linearly interpolated between the
two colors. (Specifically, each of the three color components (i.e., red, green, and
blue) will be interpolated to result in the cursor’s color for a given Z position.)

Control Signal
Cursor movement is controlled by the output of the Signal Processing Module. In
this signal, channels 1, 2, and 3 correspond to dimensions X, Y, and Z, and there
is a single value (element) present in each channel, defining cursor velocity in the
respective dimension. Additional channels or elements that might be present in the
control signal will be ignored by the CursorTask application module.

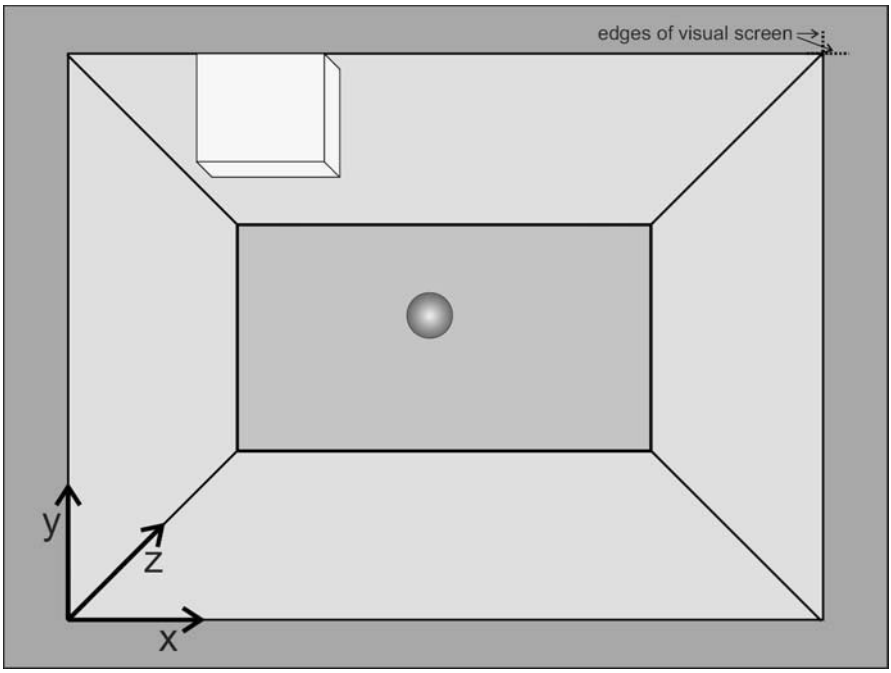

Fig. 10.12 Visual display of the Cursor Task

10.8.1.1 Parameters

Positions and sizes are given in a percent coordinate system. There, `[ 0 0 0 ]` corresponds to the bottom left corner of the workspace, and `[100 100 100]` corresponds to its diagonal counterpart.

CameraAim Camera aim point in percent coordinates.
CameraPos Camera position vector in percent coordinates of the 3D area.
CameraProjection An enumerated value that specifies one of the following camera projections:

- 0: flat,
- 1: wide angle perspective,
- 2: narrow angle perspective.

CursorColorFront, CursorColorBack The cursor's color when it is in the front or back of the workspace, given as an RGB value. When different colors are specified for front and back, the cursor's z coordinate will be used to linearly interpolate between the two color values.
CursorPos The cursor's starting position, given as a vector in percent coordinates.
CursorTexture The path to a texture file to be used for the cursor.
CursorWidth The feedback cursor's width, given in percent of screen width.

FeedbackDuration Typical duration of feedback. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar. This parameter is not a hard limit to feedback duration but determines cursor velocity such that, for a normalized control signal, cursor movement will take the specified time from the cursor’s starting point to the screen’s edge. Feedback trials will typically have this duration, provided that the cursor starts at the center of the screen, targets are located at the screen’s edges, and cursor and target width are ignored (for further details, see the section on the Normalizer above).

ITIDuration The duration of the inter-trial interval. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar.

LightSourcePos Light source position in percent coordinates.

LightSourceColor The light source’s color in RGB encoding.

MaxFeedbackDuration Abort a trial after this amount of feedback time has expired. Unlike the FeedbackDuration parameter, this is a hard limit. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar.

MinRunLength The duration of a run, i.e., the time corresponding to a continuously recorded data file. A run will not stop during a trial, so its actual length may be larger than this value by the length of a trial. If this parameter is set, then NumberOfTrials should be blank, and vice-versa. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar.

NumberTargets The number of targets on the feedback screen.

NumberOfTrials The number of trials in a run. If this parameter is set, then MinRunLength should be blank, and vice-versa.

PreFeedbackDuration The duration of target display before feedback begins. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar.

PreRunDuration The duration of the pause preceding the first trial. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar.

PostFeedbackDuration The duration of result display after feedback. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar.

RenderingQuality An enumerated value with one of the following entries:

- 0: low – 2D rendering. Lighting, shading, and textures are switched off, even if specified otherwise for individual objects. Also, collision detection ignores objects’ z positions. On machines without OpenGL compatible 3D hardware, 2D rendering is considerably faster than 3D rendering.
- 1: high – 3D rendering. Lighting, shading, and textures are applied as specified.

TargetColor Target color in RGB encoding.

Targets A matrix with six columns. The first three columns define the position coordinates of the target’s center, given in percent coordinates; the last three columns

define the target's three-dimensional extent (i.e., width, height, depth, respec-
tively). Each row corresponds to one target. Targets are always cuboids aligned
with the three coordinate axes.

TargetTexture Path to a texture file to be used for targets, or empty for none. Cur-
rently, Windows BMP files are accepted as textures. Paths may be absolute, or

relative to the executable's working directory at startup, which usually matches the executable's location.

TestAllTargets An enumerated value that determines collision test behavior:

- 0 to test only the visible current target,
- 1 to test all targets.

WindowBitDepth The feedback window's color bit depth.

WindowWidth, WindowHeight The width and height of the subject-visible application window, in pixels.

WindowLeft, WindowTop The screen position of the application window's top left corner, in pixels.

WorkspaceBoundaryColor The workspace boundary color in RGB encoding. The special value of `0xff000000` hides the workspace boundary.

WorkspaceBoundaryTexture The path to a workspace boundary texture, or empty. Currently, Windows BMP files are accepted as textures. Paths may be absolute, or relative to the executable's working directory at startup, which usually matches the executable's location.

10.8.1.2 States

CursorPosX, CursorPosY, CursorPosZ These states record the cursor's position, translated into the 0–4,095 range such that the 3D scene's left, top, and down planes all correspond to 0, and the right, bottom, and up planes correspond to 4,095.

Feedback This state's value is 1 when the cursor is displayed on the feedback screen. Typically, this also implies that the cursor moves according to the control signal.

ResultCode At the end of a feedback trial, ResultCode is set to the target code of the outcome, i.e., the target that was hit by the cursor. When a time of PostTrialDuration has passed, ResultCode is reset to zero.

StimulusTime A 16-bit time stamp in the same format as the SourceTime state. This time stamp is set immediately after the application module has updated the stimulus/feedback display.

TargetCode During a feedback trial, this state indicates the target that is visible and that the cursor is supposed to hit. A TargetCode value of zero indicates that no target is on the screen. When TargetCode switches from zero to nonzero, the trial begins.

10.8.2 Stimulus Presentation

The main purpose of this task is to present a sequential series of auditory and/or
visual stimuli to the user. Thus, this StimulusPresentationTask is suited to implement a wide array of studies including evoked response (ERP) paradigms

or motor movement/imagery sessions. In addition to stimulus delivery, the task
can also be used in conjunction with BCI2000's P300 Signal Processing module
(`P3SignalProcessing.exe`) to provide feedback to a selected stimulus in either a copy or a free mode.

10.8.2.1 Parameters

AudioSwitch A boolean parameter to globally switch presentation of audio stimuli on or off. To present audio for individual stimuli only, remove audio entries for other stimuli from the Stimuli matrix.

AudioVolume The volume for audio playback, in percent of maximum volume. This parameter's value may be overridden by an additional row in the Stimuli, FocusOn, and Result matrices.

BackgroundColor The background color of the stimulus rectangle, given as an RGB value. The height of the rectangle is defined by the CaptionHeight parameter, and its width depends on the caption's text width.

CaptionColor For text stimuli, the color of the stimulus' caption, given as an RGB value. This parameter's value may be overridden by an additional row in the Stimuli, FocusOn, and Result matrices, as described further below.

CaptionHeight For text stimuli, the height of the stimulus' caption in percent of screen height. This parameter's value may be overridden by an additional row in the Stimuli, FocusOn, and Result matrices.

CaptionSwitch A boolean parameter to globally switch presentation of stimulus captions on or off. To present captions for individual stimuli only, remove captions for other stimuli from the Stimuli matrix.

DisplayResults Switches result display of copy/free spelling on or off.

FocusOn In copy mode (see InterpretMode), the attended stimulus is presented prior to the stimulus sequence (PreSequenceTime), preceded with a special announcement stimulus. This stimulus' properties are defined by the FocusOn parameter, which is a matrix in the same format as the Stimuli parameter. Usually, this matrix has a single column; when multiple columns are present, all stimuli are presented concurrently.

IconSwitch A boolean parameter to globally switch presentation of icon stimuli on or off. To present icons for individual stimuli only, leave icon entries for other stimuli blank in the Stimuli matrix.

InterpretMode An enumerated value that determines whether this task should be used in conjunction with the P3SignalProcessing module for on-line classification

of evoked responses:

- 0: no target is announced “attended,” signal processing classification results are ignored;
- 1: online or free mode: classification is interpreted to show the selected stimulus, but no “attended target” is defined;
- 2: copy mode: “attended” targets are defined, classification is interpreted, and selected stimulus is shown.

ISIMinDuration, ISIMaxDuration Minimum and maximum duration of the inter-stimulus interval. During the inter-stimulus interval, the screen is blank, and audio is muted. Actual inter-stimulus intervals vary randomly between minimum and maximum value, with uniform probability for all intermediate values. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar. Note that temporal resolution is limited to a single sample block.

NumberOfSequences The number of sequence repetitions in a run (a run corresponds to a single data file).

PostRunDuration Duration of the pause following last sequence. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar.

PostSequenceDuration Duration of the pause following sequences (or sets of intensifications). Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar. When used in conjunction with the P3TemporalFilter, this value needs to be larger than the EpochLength parameter. This allows classification to complete before the next sequence of stimuli is presented.

PreRunDuration The duration of the pause preceding the first sequence. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar.

PreSequenceDuration Duration of the pause preceding sequences (or sets of intensifications). Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar. In free or copy mode, the PreSequenceDuration and PostSequenceDuration parameters may not go below twice the value of the StimulusDuration parameters, in order to allow for presentation of FocusOn and Result announcement stimuli.

Result In copy and free modes (see InterpretMode), the classification result is presented following the sequence (PostSequenceTime). Presentation of the predicted stimulus is preceded with an announcement stimulus. This stimulus’ properties are defined by the Result parameter, which is a matrix in the same format as the Stimuli and FocusOn parameters.

Sequence In deterministic mode, a list of stimulus codes that define the sequence of presentations. In random mode, a list of integer stimulus frequencies.

SequenceType Enumerated value that can be:

- 0: deterministic sequence mode: the sequence is explicitly defined in the Sequence parameter;

- 1: random sequence mode: the sequence is random, with pre-defined stimulus frequencies.

Stimuli A matrix that defines the stimuli and their properties. Columns of the Stimuli matrix correspond to individual stimuli and their stimulus codes. For each stimulus, the following properties are defined by its row entries:

- Caption: a text string, with its size and color depending on the CaptionHeight and CaptionColor parameters;
- Icon: a graphic file (Windows BMP), with its size depending on the StimulusWidth parameter;

- Audio: an audio file (Windows WAV), with playback starting at the onset of the visual stimuli.

A blank entry for caption/icon/audio is accepted, and implies that no presentation of the respective element takes place.

Additionally, a number of global stimulus parameters may be overridden with specific values for individual stimuli. To do this, for each parameter to be individualized, add an additional row to the Stimuli matrix. The row label indicates the parameter to be changed, and has to be one of:

- StimulusDuration,
- ISIMinDuration, ISIMaxDuration,
- StimulusWidth, CaptionHeight, CaptionColor, AudioVolume.

Whenever one of these rows is present, the corresponding global parameter will be ignored.

StimulusDuration For visual stimuli, the duration of stimulus presentation. For auditory stimuli, the maximum duration, i.e., playback of audio extending above the specified duration will be muted. Given in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar.

StimulusWidth For icon stimuli, stimulus width in percent of screen width. Stimulus height is deduced from the stimulus’ aspect ratio, which is always conserved. If this parameter is zero, all stimuli will be displayed unscaled, i.e., at their original pixel size. This parameter’s value may be overridden by an additional row in the Stimuli, FocusOn, and Result matrices.

ToBeCopied A list of stimulus codes that define a sequence of attended stimuli. At the beginning of each presentation sequence, another entry from this list is announced as the attended stimulus (see FocusOn). This parameter is only used in copy mode.

UserComment An arbitrary string intended for documentation purposes.

WindowBackgroundColor The window’s background color, given as an RGB value. For convenience, RGB values may be entered in hexadecimal notation, e.g., `0xff0000` for red.

WindowLeft, WindowTop The screen position of the application window’s top left corner, in pixels.

WindowWidth, WindowHeight The width and height of the subject-visible application window, in pixels.

10.8.2.2 States

PhaseInSequence This state is 1 during pre-sequence, 2 during sequence and 3 during post-sequence (see Timeline).

SelectedStimulus When classification is performed, this state contains the stimulus code of the stimulus classified as the “selected” one.

StimulusBegin This state is 1 during the first block of stimulus presentation, and 0 otherwise.

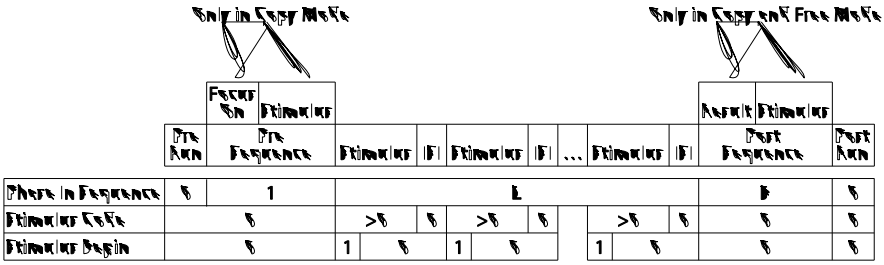

Fig. 10.13 Timeline for the Stimulus Presentation task

StimulusCode The numerical ID of the stimulus being presented (16 bit).
StimulusTime A 16-bit time stamp in the same format as the SourceTime state.
This time stamp is set immediately after the application module has updated the stimulus/feedback display.
StimulusType This state is 1 during presentation of an attended stimulus, and 0 otherwise. The notion of an “attended” stimulus requires data recording in copy mode.

The time line of this task, as well as corresponding state values, are shown in Fig. 10.13.

10.8.2.3 Stimulus Presentation Remarks

Stimulus Definition
Stimuli are set up through a parameter defined by the application module. This implicitly defines the total number of stimuli as well as the details of each stimulus.
Each stimulus is defined by the following properties:

1. Caption
2. Icon file
3. Audio file

In addition to stimuli that are part of the actual stimulation sequence, the Focus-On and Result parameters contain definitions for a stimulus that indicates what to focus on, and a stimulus that presents the result. These stimuli are only used when the task is set to copy or free mode. The following table contains an example definition of two stimuli:

	stimulus1	stimulus2
Caption	Donkey	

Icon	images/donkey.bmp	images/elephant.bmp
Audio	sounds/snicker.wav	sounds/trumpet.wav

A blank entry for caption/icon/audio file is accepted, and implies that no presentation of the respective element takes place (e.g., see “Caption” in stimulus2). The

stimulus definition parameter does not contain a description on how the stimuli are
presented. For further details, see the Stimuli parameter description.

Stimulus Codes
When defining a stimulus sequence, stimuli are referred to an integer ID called
stimulus code. The stimulus code associated with a stimulus corresponds to the
column in which that stimulus is defined in the Stimuli matrix parameter. In the
recorded data file, stimulus presentation is indicated by the StimulusCode state.
During presentation of a stimulus, this state is set to the associated stimulus code.

Stimulus Sequence
Stimuli are presented in a certain sequence. This sequence can either be deterministic, i.e., defined by the investigator, or pseudo-random.

Deterministic Sequence
The investigator defines the order by entering a list of stimulus IDs to be presented. As an example, 1 5 3 4 2 defines a sequence in which stimulus 1 is presented first, followed by stimulus 5, etc.

Random Sequence
The investigator defines absolute stimulus frequencies for each stimulus, with the
sum N of those values equaling the total number of stimulus presentations in the final sequence. The resulting random sequence is obtained by applying a random permutation to an arbitrary sequence that reproduces the given frequencies, and where
all N! index permutations are equally probable (block randomization).

As an example, 6 2 3 defines a sequence of 11 stimulus presentations with stimulus one being presented 6 times, stimulus two 2 times, and stimulus three
3 times. The resulting sequence will be a permutation of S_0 = [1,1,1,1,1,1,2,2,3, 3,3].

Multiple sequences can be generated from the given frequencies. The investigator can define how many sequences are generated and presented.

Stimulus Delivery
For any stimulus, delivery occurs simultaneously for caption, icon, and audio. When both caption and icon are defined, the caption appears overlaying the icon.

An investigator can specify:

- Size and position of the target window.
- Width and height of caption and icon in percent of screen width/height, or that the icon should appear in its original pixel size.
- Whether captions, icons, or audio files will be presented (i.e., a global switch).

There are no individual switches for each stimulus. However, individual captions/icons/wave files are not presented if they are not defined (i.e., their respective entries are blank).

- The volume for audio playback as a percentage of maximum volume.
- Window background color in RGB. (For convenience, RGB values may be entered in hexadecimal notation, e.g., `0xff0000` for red.)

- Caption color in RGB.
- The duration of stimulus presentation. (Playback of audio extending above the specified duration will be muted.)
- The duration of an inter-stimulus interval following stimulus presentation. (During the inter-stimulus interval, the screen is blank and audio is turned off.)
- Variance in inter-stimulus intervals, with probability distributed uniformly over the interval between minimum and maximum inter-stimulus interval.
- For documentation purposes, a user can enter a comment to the specific run in a string parameter.

Processing of Classification Results

The task can be configured to interpret results communicated to it by the P3 Signal Processing module. These results represent a judgment of which of the stimuli was most likely selected. Handling of these results is identical to the P300 Speller.

When it transmits a classification result, Signal Processing sets the state StimulusCodeRes to the stimulus code that was originally transmitted to it by the user application. For example, when Signal Processing sets StimulusCodeRes to 3, it transmits classification results for stimulus 3. In addition, it sets StimulusTypeRes to reflect the type of stimulus (0 = non-target, 1 = target) when the system is in copy mode. Signal Processing transmits the classification result as one number (i.e., the first control signal).

Free Mode

The task can be configured to operate in free mode. In this case, the sequence of stimulus deliveries is followed by a time period during which the Signal Processing classification result is presented. The final classification result is the stimulus with the highest classification result.

In order to present this result, the system uses the stimulus defined in the result column of the stimuli parameter. This presentation is followed by delivery of the determined stimulus. In other words, after a sequence of stimulus deliveries, the system might play a .wav file that says: “the result is,” followed by a .wav file that says “yes.” (assuming “yes” represents the stimulus that produced the highest

classification result).

Finally, the task sends this result to the Operator module as an ASCII text message so that it appears in a log window. Free mode does not terminate until the investigator suspends operation.

Copy Mode

Copy mode is similar to free mode. In copy mode, the investigator can define a list of stimuli to be copied (e.g., 3 5 4). In this example, the user has to attend to stimulus 3 for the first sequence, 5 for the second sequence, etc.

In addition to presenting the result, the delivery of stimuli is preceded by a presentation that describes the stimulus to which the user must attend. This presentation uses the stimulus that is defined in the FocusOn parameter. This presentation is followed by delivery of the desired target stimulus. As an example, the system

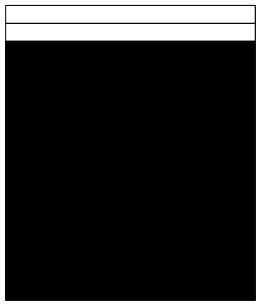

Fig. 10.14 An exemplary 6 by 6 speller matrix. Here, the user's task is to spell the word "SEND" (one character at a time). For each character, all rows and columns in the matrix are intensified a number of times. In this example, the third row is intensified

might say "Please focus on" ... "yes," before it starts with the sequence of stimulus deliveries.

Copy mode terminates (i.e., suspends the task) when the user has finished copying all stimuli specified by the investigator.

10.8.3 P300 Speller

The P3SpellerTask implements Donchin's matrix speller paradigm [1, 4]. The most typical configuration is a 6 by 6 matrix (see Fig. 10.14). The user's task is to focus attention on characters in a word that is prescribed by the investigator (i.e., one character at a time) and displayed on the user's screen. Alternatively, the user may freely choose letters he/she attends to, using the speller as a true communication device.
All rows and columns of this matrix are successively and randomly intensified. For a full set of intensifications of rows or columns, two contain the desired character (i.e., one particular row and one particular column). The responses evoked by these infrequent stimuli are different from those evoked by the stimuli that did not contain the desired character, in a manner similar to the classical P300 paradigm [4]. The entire set of stimuli is usually flashed several times before the P3SpellerTask calculates the desired character. To ensure optimal amplitudes of the evoked responses, it is important that the stimuli are infrequent even between sequences. Therefore, the P3SpellerTask avoids starting a sequence with the row or column that was intensified last in the previous sequence. By determining the row/column with the

strongest response, the speller derives which of the matrix elements the subject
wanted, and executes the action corresponding to that matrix element. Typically,
this action will consist in adding a character to a text window. Beyond the basic
features, the P3SpellerTask provides the ability to handle multiple speller menus,
saving and recovering the text buffer, and an option to exchange information with
an external program. Typically, the P3SpellerTask is used in conjunction with the
P3TemporalFilter signal processing filter/P3SignalProcessing signal processing module.

10.8.3.1 Parameters

AudioStimuliOn Switches playback of audio stimuli on or off.

AudioStimuliRowsFiles, AudioStimuliColsFiles Each of these parameters is a single-column matrix specifying audio files associated with speller rows or columns, respectively. Whenever a row/column is highlighted, the associated audio file is played back. For audio files, Windows WAV format is expected. Paths may be absolute, or relative to the executable's working directory at startup, which usually matches the executable's location. Rather than the path to an audio file, text may be given, enclosed in single quotes. In this case, the text is rendered using the system's Text-To-Speech engine.

BackgroundColor Matrix elements' background color, given in RGB encoding.

DestinationAddress A network address to receive speller output, given in `IP:port` format, e.g., `localhost:3582`. A UDP socket is opened to this address; the program then sends information about selected matrix elements to the external application. For each selection, the speller will write whatever is contained in the selected matrix element's Enter field, preceded with `P3Speller_Output` and a space character, and followed with a `\r\n` sequence (i.e., an MS-DOS style line ending). E.g., the output will be `P3Speller_Output A\r\n` when a matrix element is selected that enters the letter "A," and `P3Speller_Output <BS> \r\n` for a matrix element corresponding to the backspace command.

DisplayResults Switches result display of copy/free spelling on or off.

FirstActiveMenu For multiple menus, the index of the menu that should be active at the start of a run.

IconHighlightFactor If IconHighlightMode is 1 or 4, this parameter defines the brightness scaling factor. Dimming is equivalent to intensifying with a scaling factor less than 1.

IconHighlightMode An enumerated value that specifies how icons are highlighted on stimulus presentation:

- 0: Show/Hide: icons are only visible during stimulus presentation,
- 1: Intensify: highlight by increasing icon brightness,
- 2: Grayscale: display a grayscale version during stimulus presentation,
- 3: Invert: invert color/brightness values during stimulus presentation,
- 4: Dim: decrease brightness during presentation.

InterpretMode An enumerated value selecting on-line classification of evoked responses:

- 0: no target is announced "attended," and no classification is performed;
- 1: online or free mode: classification is performed, but no "attended target" is defined;
- 2: copy mode: "attended" targets are defined, classification is performed.

ISIMinDuration, ISIMaxDuration Minimum and maximum duration of the

inter-stimulus interval. During the inter-stimulus interval, the screen is blank, and
audio is muted. Actual inter-stimulus intervals vary randomly between minimum
and maximum value, with uniform probability for all intermediate values. Given
in sample blocks, or in time units when immediately followed with ‘s,’ ‘ms,’ or similar. Note that temporal resolution is limited to a single sample block.

NumberOfSequences The number of intensification sequences performed prior to each classification (selection of matrix elements). For an N × M speller matrix, a single intensification sequences comprises N + M intensifications, one for each row, and one for each column. Usually, this parameter is set to the same value as the P3TemporalFilter's EpochsToAverage parameter.

NumMatrixColumns, NumMatrixRows The number of columns/rows in the speller matrix. For Multiple Menus, a list of numbers representing each menu's number of columns/rows.

PostRunDuration Duration of the pause following last sequence. Given in sample blocks, or in time units when immediately followed with 's,' 'ms,' or similar.

PostSequenceDuration Duration of the pause following sequences (or sets of intensifications). Given in sample blocks, or in time units when immediately followed with 's,' 'ms,' or similar. When used in conjunction with the P3TemporalFilter, this value needs to be larger than the EpochLength parameter. This allows classification to complete before the next sequence of stimuli is presented.

PreRunDuration The duration of the pause preceding the first sequence. Given in sample blocks, or in time units when immediately followed with 's,' 'ms,' or similar.

PreSequenceDuration Duration of the pause preceding sequences (or sets of intensifications). Given in sample blocks, or in time units when immediately followed with 's,' 'ms,' or similar. In free or copy mode, the PreSequenceDuration and PostSequenceDuration parameters may not go below twice the value of the StimulusDuration parameters in order to allow for presentation of FocusOn and Result announcement stimuli.

StatusBarSize, StatusBarTextHeight The size and text height of the status bar in percent of screen height. The status bar is located on top of the screen, and displays the text that has been spelled so far. In copy mode, it also displays the text that the user is supposed to spell.

StimulusDuration For visual stimuli, the duration of stimulus presentation. For auditory stimuli, the maximum duration, i.e., playback of audio extending above the specified duration will be muted. Given in sample blocks, or in time units when immediately followed with 's,' 'ms,' or similar.

TargetDefinitions A five-column matrix defining elements of the speller matrix. Each row corresponds to a single matrix element; matrix elements are enumerated row-wise, beginning with the top left matrix element. The columns of the definition matrix are:

1. Display: A text string to be displayed in the matrix element, i.e., the matrix
element's caption.
2. Enter: Specifies the speller action to be performed upon the item's selection;
in most cases, this action consists in entering a text string, and is specified by
that string. E.g., for the top left matrix element to display the caption "A", and
also enter the letter "A" on selection, both the Display and Enter columns will
contain the letter "A."

3. Size: Specifies an individual size for the matrix element, relative to the size of the other matrix elements.
4. Icon File: Contains the path to an icon file to be displayed in the speller matrix element. Windows BMP format is accepted.
5. Sound: Contains the path to a sound file to be played when the matrix element is selected. Sounds are given as a path to a Windows WAV file, or as a text enclosed in single quotes. When a text is given, it will be spoken using the system's Text-To-Speech engine.

TargetTextHeight Matrix elements' text height in percent of screen height.
TargetWidth, TargetHeight A single matrix element's width/height in percent of screen width/height.
TestMode If this parameter is selected, clicking on a matrix element with the mouse will select it once the current sequence of intensifications is finished. This is useful to test speller matrix configurations.
TextColor, TextColorIntensified Text color in standard and highlighted (intensified) mode, given in RGB encoding.
TextResult At the beginning of a run, this parameter's content is copied into the lower part of the status bar. At the end of a run, the status bar's content is copied back into this parameter.
TextToSpell In copy mode, a string of characters defining the text to be spelled by the user. This text is displayed in the status bar, above the actually spelled text.
From the difference between TextToSpell, and the actually spelled text, the speller automatically derives which matrix element the user will need to select next. This information is then used to set the StimulusType state.
TextWindowEnabled If this parameter is selected, a separate window is displayed. Once the status bar is filled, text flows into the window, and back in case of text deletion.
TextWindowFilePath A (relative or absolute) path to a directory. Upon the <SAVE> and <RETR> speller commands, the text window's contents are saved to/retrieved from a file located in that directory. Repeated <SAVE> commands do not result in overwriting existing files. Rather, existing files are preserved, and the most recent file's name is written into a pointer file. Paths may be absolute, or relative to the executable's working directory at startup, which usually matches the executable's location.
TextWindowFontName, TextWindowFontSize Text window font name and size.
TextWindowLeft, TextWindowTop, TextWindowWidth, TextWindowHeight

Position and dimension of the text window in pixels.

WindowBackgroundColor The window's background color, given as an RGB value. For convenience, RGB values may be entered in hexadecimal notation, e.g., `0xff0000` for red.

WindowLeft, WindowTop The screen position of the application window's top left corner, in pixels.

WindowWidth, WindowHeight The width and height of the subject-visible application window, in pixels.

10.8.3.2 States

PhaseInSequence This state is 1 during pre-sequence, 2 during sequence and 3 during post-sequence (see the timeline above).

SelectedTarget, SelectedRow, SelectedColumn Upon classification, these states are set to the selected target's ID, and its associated row and column, respectively. A target's ID matches its row number in the TargetDefinitions matrix.

StimulusBegin This state is 1 during the first block of stimulus presentation, and 0 otherwise.

StimulusCode The numerical ID of the stimulus being presented (16 bit).

StimulusTime A 16-bit time stamp in the same format as the SourceTime state. This time stamp is set immediately after the application module has updated the stimulus/feedback display.

StimulusType This state is 1 during presentation of an attended stimulus, and 0 otherwise. The notion of an "attended" stimulus requires data recording in copy mode.

10.8.3.3 P300 Speller Remarks

Speller Commands

Speller commands are specified in the second column of the TargetDefinitions matrix. Speller commands may be sequences of characters, which are added to the speller text when the respective item is selected. Additionally, speller commands may be speller control commands enclosed in a pair of < > characters.

Any combination of characters and commands is allowed, and will be executed in sequence.

Available speller control commands are:

- <BS> (backspace) – delete the last character from the current text.
- <DW> (delete word) – delete the last word from the current text.
- <UNDO> – undo the effect of the previous speller action.
- <END> – end spelling, put BCI2000 in suspended mode.
- <SLEEP> – suspend spelling; resume when <SLEEP> is selected two additional times.
- <PAUSE> – suspend spelling; resume when <PAUSE> is selected again.
- <GOTO x> – go to speller menu number x (see Multiple Menus below).
- <BACK> – return to the previously active speller menu.
- <SAVE> – write the text window's content into a file located at TextWindow-

FilePath.

- <RETR> – load the text window’s content from the most recently saved file.

Multiple Menus

The P3SpellerTask allows you to specify a number of speller menus, and to switch between them using the <GOTO> and <BACK> speller commands. For multiple speller menus, the TargetDefinitions matrix needs to be configured as a list of

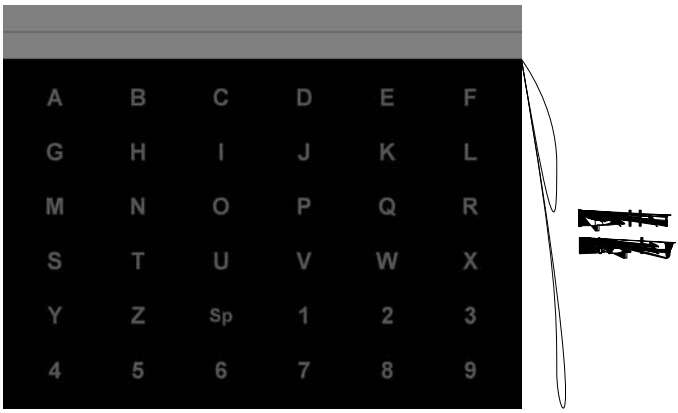

Fig. 10.15 Elements of the user's screen. The Text To Spell field indicates the pre-defined text.
The speller will analyze evoked responses, and will append the selected text to Text Result

matrices rather than a single matrix. Then, each submatrix should have the form described above. Each of the submatrices may have an individual number of rows and columns and its own set of matrix elements. Also, switching to Multiple Menus implies additional entries in the following parameters:

- NumMatrixColumns, NumMatrixRows
- AudioStimuliRowsFiles, AudioStimuliColsFiles (additional columns)
- TargetWidth, TargetHeight, TargetTextHeight, BackgroundColor
- TextColor, TextColorIntensified, IconHighlightMode, IconHighlightFactor

Visual Representation
The visual representation is divided into three parts (Fig. 10.15):

Text to Spell displays the text that the user needs to spell (only used in copy spelling mode).
Text Result holds the letters spelled up to the current moment.
Speller Display is the area that contains the speller matrix.

In addition to the text characters, it is possible to display icons (bitmaps) in the P3Speller matrix. This can be achieved by entering the appropriate file name for the icon in column 4 of the desired cell in the TargetDefinition parameter. The icon will be flashed (highlighted) using a number of methods (see the description of the IconHighlightMode parameter above). As new characters are added to the right, the Text Result area gets filled; once there is no space left, the text is scrolled to the left in order to accommodate additional characters.

It is also possible to play a sound file or to "speak" text (using a Text-to-Speech

engine) when a cell is selected. To play a sound file, the sound file name should
be entered in column 5 of the desired cell in the target definition matrix. To enable
a text-to-speech function, the text to be “spoken” should be entered in column 5
of the desired cell in the target definition matrix within single quotes (e.g., ‘text’),

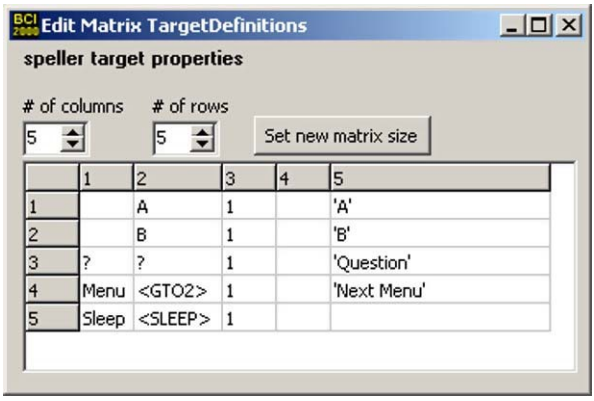

Fig. 10.16 Example for a target definition matrix

as in Fig. 10.16. The Text-to-Speech engine uses the system's "default voice" setting (Control Panel → Speech → TextToSpeech → Voice Selection). Male or female voices may be selected.

Testing Matrix Menus
In order to test matrix menu configurations, the P3SpellerTask may be put into a test mode. In this mode, mouse clicks into matrix elements are registered during sequence presentation, and force selection of the respective matrix element.

Pause and Sleep
There are two speller commands that allow the user to suspend operation of the P3SpellerTask either momentarily or for an extended period of time, <PAUSE> and <SLEEP>. To associate speller commands with certain matrix elements, specify them in the "Enter" column of the desired matrix element in the target definition matrix. The <PAUSE> speller command pauses the P3SpellerTask: While the system is paused, the matrix will continue to flash but target selections are ignored until the user resumes system operation, which is achieved by selecting <PAUSE> again. Data recording is also suspended while the system is paused. The goal text line of the status bar indicates that the system is paused. For a matrix with N entries (one of which is <PAUSE>), the chance to erroneously resume system operation while paused is $\frac{1}{N}$ per selection. On average, this will happen after N selections in paused state. A second speller command, <SLEEP>, is provided as a safer option. Once in sleep state, the system will resume only after receiving two consecutive <SLEEP> selections, which requires N^2 selections on average to occur by chance. When in sleep mode, the goal text line of the status bar will instruct the user to select the

<SLEEP> command twice to restart.

Text Window

The capability to display user selected text in a text window is available. This fea-
ture can be activated by selecting the TextWindowEnabled parameter. The text

window can be enabled only in online (free spelling) mode. Position and size of the window, as well as display font, are configurable. When the text window is enabled, any text that the user selects will appear in the text window, in addition to the text result area of the P3SpellerTask display. The text window will scroll automatically.

Two speller commands are available to perform Save and Retrieve operations on the text window. When the <SAVE> command is selected, the text in the text window will be written to a file and be erased from the window. The file name will be auto generated with the date and time stamp. The directory to which the file gets sent is configured in the TextWindowFilePath parameter. The <RETR> (retrieve) function reads the latest file that was saved by the user and recalls the text into the text window. A separate clear command has not been provided in the text window functions to prevent unintentional deletion of its contents. The only way to clear the contents of the text window is using <SAVE>.

Nested Matrices

To allow for more flexibility in real-world applications, multiple speller matrices can be specified, and may be traversed in a “nested” manner. For example, one of the cells in the first matrix may be tied to another matrix which is displayed when this cell is selected by the user. This capability may be used to design a menu-based user interface.

To use the nested menu capability, the following steps need to be executed:

Set up the Target Definition Matrix To maintain backward compatibility and for ease of configuration, the application will not support nested functionality by simply converting one cell of the old target definition matrix to a sub-matrix. To define nested matrices, the TargetDefinition parameter must be defined with one column and each cell as a sub-matrix. If it has more than one column, the application will treat it as a single matrix and will ensure that each of its cells is defined as a single value.

Convert Each Cell to a Sub-matrix In the GUI, this is done by right-clicking on each cell as shown in Fig. 10.18, and choosing “Convert to sub-matrix” from the context menu.

Configure Individual Sub-matrices Each cell in a nested matrix is a sub-matrix (as shown in Fig. 10.17) and needs to be configured individually. In the GUI, click-

ing on a cell that is a sub-matrix will bring up that matrix in another window, as shown in Fig. 10.19. Each sub-matrix should be configured to have a minimum of three columns and can have up to five columns if it needs to display icons or play sounds.

Enable Transition from One Menu to Another Special control codes (speller commands) allow transition from one matrix to another. To go to a different matrix when an item is selected, enter the <GOTO#> command into its “Enter” column, replacing “#” with the (one-based) index of the corresponding matrix (menu). The <BACK> (or <BK>) command will go back to the previous menu/matrix (see Fig. 10.19).

Number of Rows and Columns of Each Nested Menu (Matrix) The number of rows and columns in each sub-matrix needs to be entered into the NumMa-

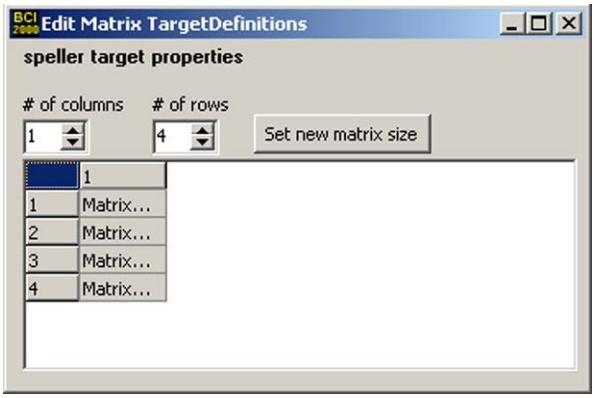

Fig. 10.17 Example for a target definition matrix for four nested menus

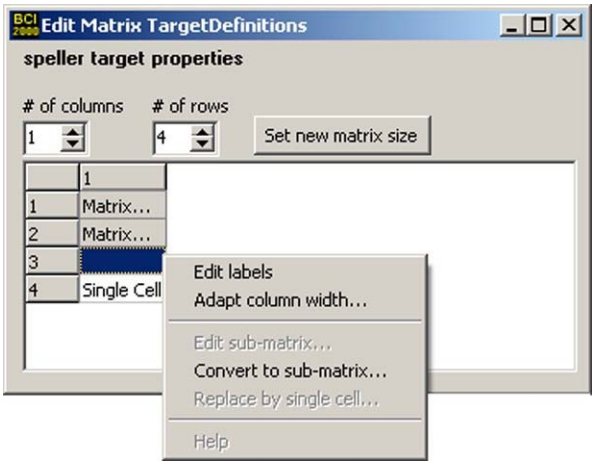

Fig. 10.18 Converting cells to sub-matrices

trixRows and NumMatrixColumns parameters. There, individual entries are separated by space characters. Figure 10.20 indicates that the first three sub-matrices
are 2×2, while the sub-matrix at index 4 is a 6×6 matrix. In case of a single
(non-nested) matrix, there will be only one entry in the NumMatrixRows and NumMatrixColumns parameters.

Select First Menu to Be Displayed The index of the menu to be displayed first (i.e., when the application is started) is entered in the FirstActiveMenu parameter.
In case of non-nested matrix configuration, this parameter should be left at its
default value of 1.

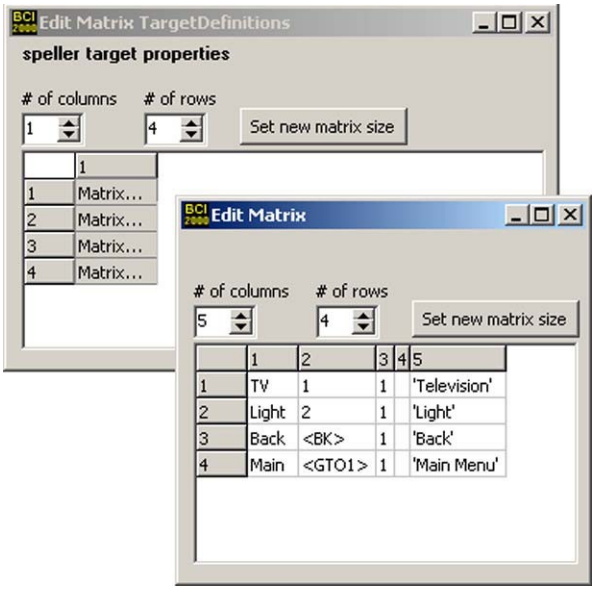

Fig. 10.19 Configuring individual sub-matrices

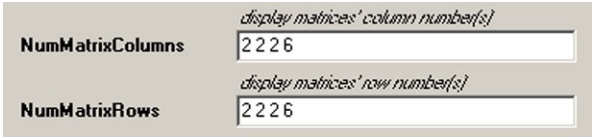

Fig. 10.20 Rows and columns of each sub-matrix

10.8.4 Keystroke Filter

The KeystrokeFilter translates BCI2000 state changes into simulated key presses.
Simulated keypresses can then be used to control an external application program
installed on the machine running the BCI2000 application module. Only the lower
4 bits of the state value are used, and translated into presses of the keys corresponding to their hexadecimal representation (`0...9, A...F`).

10.8.4.1 Parameters

KeystrokeStateName The name of a BCI2000 state to be converted into simulated keystrokes.

10.8.4.2 States

Any existing state may be given in the KeystrokeStateName parameter.

10.8.5 Connector Filters

The Connector Filters provide an implementation of the BCI2000 App Connector protocol. Typically, the ConnectorInput filter is the first filter in the Application Module, which allows external changes to BCI2000 states to affect the application module's behavior immediately. Similarly, the ConnectorOutput filter is placed last in the application module, such that state information read over the protocol will immediately reflect the application module's state changes. A description of the connector protocol, along with client example code, and configuration examples, is detailed in the App Connector section in Sect. 6.4.

10.8.5.1 Parameters

ConnectorInputAddress An `address:port` combination that specifies a local UDP socket. Addresses may be host names or numerical IP addresses. Incoming data is read from this socket.

ConnectorInputFilter For incoming values, messages are filtered by state name using a list of allowed names present in this parameter. To allow signal messages, allowed signal elements must be specified including their indices. To allow all names, enter an asterisk (*) as the only list entry.

ConnectorOutputAddress An `address:port` combination that specifies a local or remote UDP socket. Addresses may be host names, or numerical IP addresses. For each data block, values of all state variables and the control signal are written out to this socket, using the App Connector protocol.

10.8.5.2 States

All states present in the system are transmitted over the App Connector protocol.

10.9 Tools

10.9.1 BCI2000 Offline Analysis

“BCI2000 Offline Analysis” is a simple tool to analyze BCI2000 data in the time- or frequency domain. To run this tool, whose screen shot is shown in Fig. 10.21,
you’ll need a system running either Windows 2000 or later. If your system meets
this requirement, please choose from one of the following:

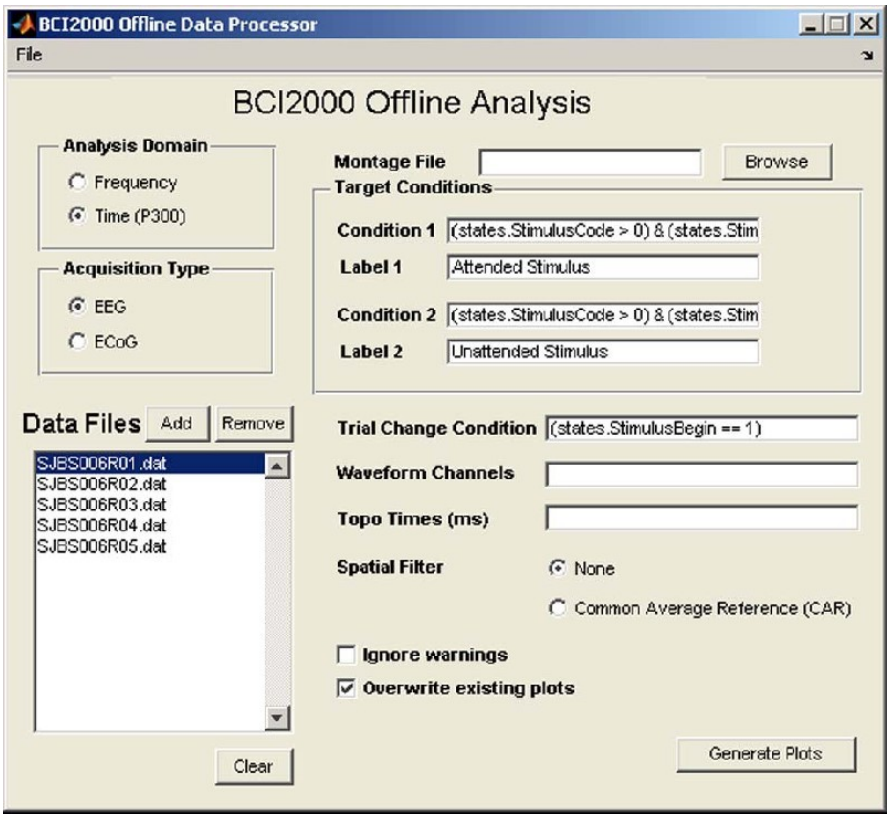

Fig. 10.21 Screen shot of the BCI2000 Offline Analysis tool

10.9.1.1 Systems with Matlab v7.0 or Greater Installed

Startup Script

If you have not yet opened Matlab, the easiest way to run `BCI2000 Offline Analysis` is to double click the OfflineAnalysis.bat file that resides in `BCI2000/tools/OfflineAnalysis/`.

From the Matlab Command Line

If MATLAB is already running, navigate to `BCI2000/tools/OfflineAnalysis/` using the “Current Directory” explorer, or type the absolute path into the textbox at
the top of the Matlab window. Then, type `OfflineAnalysis` at the MATLAB command prompt to start analyzing your data.

10.9.1.2 Systems That Do Not Have Matlab Installed or with Versions That Predate MATLAB v7.0

Offline Analysis Without Matlab

1. Download the Matlab Component Runtime (MCR) from http://www.bci2000.org/downloads/bin/MCRInstaller.exe.
2. When the download is complete, run the installer.
3. Follow the on-screen instructions to complete the installation.
4. Navigate to `BCI2000/tools/OfflineAnalysis/`.
5. Double-click `OfflineAnalysisWin.exe` to begin analyzing your data.

10.9.1.3 Reference

File>Save Settings "Save Settings" allows you to save the values you've entered for all fields excluding "Data Files," "Ignore warnings" and "Overwrite existing plots." This functionality may be particularly useful if you want to run the same or similar analyses between sessions.

File>Load Settings "Load Settings" allows you to load a settings file previously created using File>Save Settings.

Analysis Domain The BCI2000 Offline Analysis tool allows you to analyze your data either in the frequency domain or the time domain. Be aware that certain fields will be labeled differently depending on the domain that is chosen. Specifically, choosing "Frequency" will make the "Spectra Channels" and "Topo Frequencies" fields available. Choosing "Time" will make the fields "Waveform Channels" and "Topo Times" available. Additionally, the values for the target conditions, trial change condition and spatial filter will be overwritten so as to correspond with the chosen domain.

A frequency domain analysis will result in up to three plots comprising a feature map, a spectra plot (one spectrum for each channel specified) and up to nine topographic plots (one for each topo frequency specified). For EEG-based analyses, the best frequency domain features are typically found between 9–12 Hz or 18–25 Hz. Please see the user tutorial in Sect. 5.2.3 for additional information.

A time-domain analysis will result in up to three plots that consist of a feature map, a waveform plot (consisting of one waveform for each channel specified) and up to nine topographic plots (one for each topo time specified). Typically, P300 features are found at around 300 ms following presentation of the stimulus. Please see the user tutorial in Sect. 5.3.3 for additional information.

Acquisition Type Acquisition type allows the user to indicate whether the data was acquired using EEG or an ECoG.

Data Files Any number of BCI2000 data files with the same state information and number of channels may be analyzed in a single run. To select a file to add to the list of files to be analyzed, simply click the “Add” button, choose the desired file

and click “Open.” To add multiple files from the same directory, click on any one of the desired files and then control-click the additional files. Then, when all desired files are selected, click “Open.” If files have already been added to the data files list, then subsequent uses of the above procedure will append the selected files to the list allowing for addition of files from different directories.

Montage File (optional) If topographic plots are desired, you must specify a montage file that is congruent with the chosen acquisition type (i.e., EEG or ECoG).
If you do not yet have a montage file, you can create one using the “Eloc Helper” tool that comes with BCI2000 Offline Analysis. In place of a montage file, you may also use data files that specify channel names that are compliant with the 10–20 standard. In this case, “BCI2000 Offline Analysis” will use the channel name corresponding to each electrode to infer the location of that electrode.

Target Conditions Target conditions consists of four fields that allow for the specification of two different conditions. Each condition consists of the condition itself (i.e., a Matlab-syntax boolean statement) and the label for the corresponding data (e.g., “Opening and Closing Both Hands”). Typically, you will want to specify two different conditions in order to compare two different datasets. Occasionally, however, you may want to inspect a single dataset to investigate artifacts. In this case, you can omit the second condition (i.e., both the condition and the label).

Trial Change Condition The trial change condition allows for the user to specify which condition indicates a change in trials. The condition must be a Matlab-syntax boolean statement.

Spectra Channels (optional) Note: This field is available only if you’ve chosen “Frequency” as the analysis domain. If you would like to have the analysis generate spectra plots, you must enter at least one channel in this field. Multiple channels can be specified using a comma-delimited list (e.g., “1,2,3”) or a space-delimited list (e.g., “1 2 3”).

Topo Frequencies (optional) Note: This field is available only if you’ve chosen “Frequency” as the analysis domain. If you would like to have the analysis generate topographic plots, you must enter at least one frequency in this field. Multiple frequencies can be specified using a comma-delimited list (e.g., “8,11,22”) or a space-delimited list (e.g., “8 11 22”).

Waveform Channels (optional) Note: This field is available only if you’ve chosen “Time” as the analysis domain. If you would like to have the analysis generate

P300 waveform plots, you must enter at least one channel in this field. Multiple channels can be specified using a comma-delimited list (e.g., “1,2,3”) or a space-delimited list (e.g., “1 2 3”).

Topo Time (optional) Note: This field is available only if you’ve chosen “Time” as the analysis domain. If you would like to have the analysis generate topographic plots, you must enter at least one time in this field. Multiple times can be specified using a comma-delimited list (e.g., “200,300,400”) or a space-delimited list (e.g., “200 300 400”).

Spatial Filter By applying the right spatial filter to your data, you will likely be able to achieve better results. Depending on the data, however, the optimal filter will differ. “BCI2000 Offline Analysis” offers the common average reference

(CAR) filter, which is often useful if the response isn't spread out over a large number of electrodes. To apply a CAR filter to your data before processing, choose "Common Average Reference." Otherwise, choose "None" in order to run the analysis on the raw data.

Ignore warnings In order to get an accurate representation of the data, it is recommended that the analysis be performed on no less than 10 trials. "BCI2000 Offline Analysis" will generate a warning if this condition is not met. This warning can be ignored by checking this box. If a particular combination of data files and conditions results in less than three trials, an error is displayed and the analysis is halted. Errors cannot be overridden.

Overwrite existing plots Each time the analysis is run, up to three plots may be generated. If you want to compare the results from different runs, ensure that this checkbox is unchecked. In this case, "BCI2000 Offline Analysis" will generate the plots in new figures instead of simply overwriting the plots from previous analyses.

10.9.1.4 Troubleshooting

1. Clicking on any button results in the error "Undefined command/function ..." followed by "Error while evaluating figure ..." If you are receiving this error, it is possible that after opening "BCI2000 Offline Analysis" you changed Matlab's working directory. Make sure that your working directory is the same directory that contains the OfflineAnalysis script.
2. The analysis doesn't seem to be generating any topographic plots. In order to generate topographic plots, it is necessary to specify a montage file and at least one topo frequency (for frequency domain analyses) or topo time (for time domain analyses). If the analysis you are running doesn't generate a topographic plot, please ensure that you've entered values in both of these fields.
3. The analysis doesn't seem to be generating any spectra or waveform plots. To generate spectra or waveform plots, it is necessary to specify at least one spectra channel (for frequency domain analyses) or waveform channel (for time domain analyses). If your analysis is not resulting in one of these plots, please ensure that you have entered values into the appropriate field.
4. I've typed in a valid target or trial change condition, but I get the error "Invalid ... condition specified." Condition syntax is case-sensitive. For instance, while states.TargetCode may be a valid state condition, states.targetcode is not. Please double-check your conditions to ensure that the state variables are capitalized correctly.

10.9.2 USBampGetInfo

This command line tool displays all connected g.USBamps, including their serial number and the USB port that they connect to. Further, this tool reads all supported bandpass and notch filter configurations. Thus, this tool can be used to determine which filters can be used for a particular sampling frequency within BCI2000. An example screen output can be seen in Appendix A.

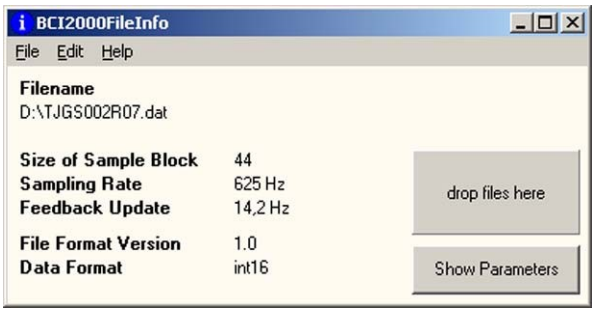

Fig. 10.22 The BCI2000FileInfo tool

10.9.3 BCI2000FileInfo

`BCI2000FileInfo` allows you to display and extract information from a BCI2000 data file. Its main window, which is shown in Fig. 10.22, displays information about a file's binary data format, sampling rate, sample block size, and
update rate.

10.9.3.1 Viewing and Saving Parameters

Clicking the Show Parameters button opens up a parameter editor similar to the
one provided by the Operator module. From there, all parameters or a subset of all
parameters may be saved into BCI2000 parameter files.

10.9.3.2 Opening Files

In addition to the File → Open... menu item, files may opened by dragging them to
the Drop Files Here area, or onto the program icon.

10.9.4 BCI2000Export

BCI2000Export (see Fig. 10.23) is a drag-and-drop-based program that allows you to import BCI2000 *.dat files into BrainProducts' VisionAnalyzer program, and to convert BCI2000 *.dat files into ASCII files.

10.9.4.1 General Usage

You may learn about the program's options by starting it and using the help hints
that appear when stopping the mouse inside one of its four main areas.

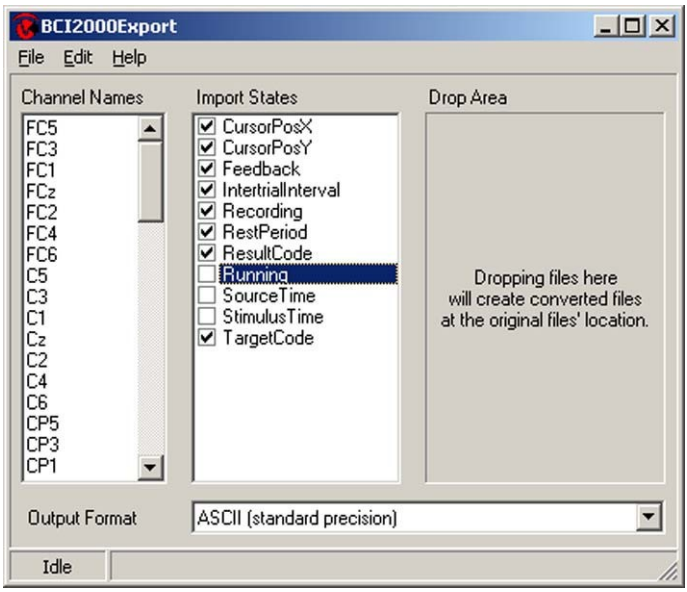

Fig. 10.23 The BCI2000Export tool

Output Format
Choose between space-delimited, tabular ASCII output and BrainVisionAnalyzer Import formats.

Importing Files
To convert files, drop them onto the “drop area” located inside its main window, or
onto its application icon. Previous settings apply; BCI2000 states not found in the
“import states” list will be added to the list and imported.

Excluding States
To populate the list of import states, drop BCI2000 files onto the “import states” list.
You can suppress the import of a state by un-checking its name in the list.

Channel Names
Channel names are given as a list of strings in the order in which the respective
channels appear in the file.

10.9.4.2 ASCII Export

An ASCII file is a space-delimited matrix with columns corresponding to channels
and states, and rows corresponding to samples. The first row is a list of column

headers.

10.9.4.3 BrainVisionAnalyzer Import

To use `BCI2000Export` most conveniently with `BrainVisionAnalyzer`, use the VisionAnalyzer's Edit Workspace... command to set the raw files folder to your BCI2000 data file folder.

BCI2000 states are mapped to the somewhat different concept of Markers used by the BrainVision software. Unlike states, which are written once for each sample, markers are given as ranges in the time domain, extending over arbitrary time intervals. In the importer program, the basic idea is to create one marker object for each state run except those runs during which the state is zero. For multi-bit states, the state's value enters into the marker's name, e.g., "Target Code 2."

10.10 Localization

Localization is the translation of messages from BCI2000's native language, English, into some other language. This is only done for messages that are visible to the experimental subject; to the operator, messages will always be displayed in English. Currently, localization support is limited to languages that allow for a standard 8-bit character representation, i.e., Western languages.

Localization is applied by matching strings against a translation table, and replacing with a localized version if available.

LocalizedStrings A matrix parameter that defines string translations. In this matrix, column labels are strings in their native (English) version; row labels are language names. When a string is to be translated, it is matched against column labels, and its translation will be taken from the row corresponding to the target language.
Strings that do not appear as a column label will not be translated. Also, strings with an empty translation entry in LocalizedStrings will not be translated.
Adding translations into another language is simple, and consists in

- adding a row to the LocalizedStrings matrix,
- labeling that row with the name of the target language,
- entering translations for the strings appearing as column titles.

Language This parameter defines the language into which strings are translated; if its value matches one of the LocalizedStrings row labels, translations will be taken from that row; otherwise, strings will not be translated. A value of `Default`

results in all strings keeping their original values.

10.11 P300 Classifier

10.11.1 Introduction

The P300 Classifier is a tool that builds and tests a linear classifier for detection of
evoked potentials (e.g., the P300 response) in data collected with BCI2000. It cur-

rently supports the P3Speller and Stimulus Presentation paradigms. The program generates the linear classifier using several methods and algorithms, most notably Stepwise Linear Discriminant Analysis (SWLDA) [2, 3, 5, 6]. The classifier derived by this program can be saved and imported into BCI2000 as a parameter file fragment (*.prm) to be used in online testing. The most common use for this program is to optimize spelling performance when using the P300 Speller module.

Unlike the Matlab-based P300 GUI that was provided with earlier version of BCI2000, the P300 Classifier is a standalone executable that does not depend on Matlab. Its core functionality is written in C++ – its graphical user interface is written using the platform independent toolkit Qt. In addition to its GUI-based functionality, the P300 Classifier program is completely scriptable, i.e., the user can execute the program using the command line and parameterize it using command line parameters. The P300 Classifier mainly realizes two functions. First, it can build a classifier using data collected using the BCI2000 P3Speller or Stimulus Presentation paradigms. Second, it can apply this classifier to data collected using these paradigms to determine classifier performance.

10.11.2 Interface

10.11.2.1 Data Pane

The P300 Classifier GUI is composed of three panes: Data, Parameters, and Details. The Data Pane shown in Fig. 10.24 allows the user to: load training and testing data files and an INI file; generate and apply feature weights; and write a parameter file fragment for use in online testing.

- Load Training Data Files: Use this button to load BCI2000 data files for classifier training. The information for the selected files will appear at the top of the button.
- Load Testing Data Files: Use this button to load BCI2000 data files for classifier testing. The information for the selected files will appear at the top of the button. Training and testing data files must be compatible.
- Load Ini File: Use this button to load an INI file that includes all classifier parameters:

```
[Initialization]

maxiter = 60 // maximum # features
```

```
penter = 0.1000 // probability for entering feature
premove = 0.1500 // probability for removing feature
spatial_filter = 1 // Spatial filter (1=RAW; 2=CAR)
decimation_frequency_Hz = 20 // decimation freq. in Hz
channel_set = 1 2 3 4 5 6 7 8 / /select channel subset
Resp_window_ms = 0 800 // response window in ms
```

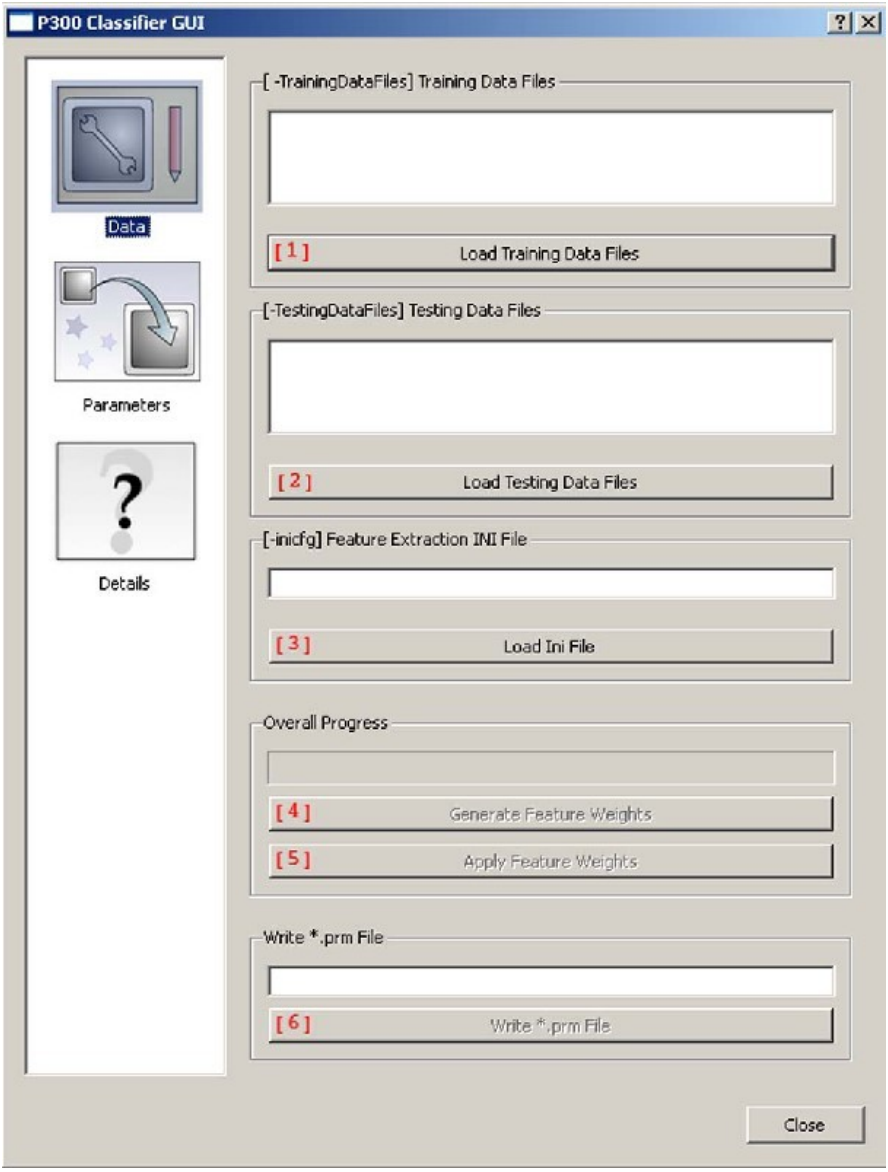

Fig. 10.24 The Data Pane in the P300 Classifier

- Generate Feature Weights: Use this button to generate the linear model, i.e., the weights for the different features (i.e., signal amplitudes at different times and channels), after properly configuring all of the parameters in the Parameters Pane. This button is enabled only if the parameters are properly configured and the training data files exist. Once the feature weights have been computed, a suggested name for the parameter file fragment (*.prm) will show up at the top of the "Write *.prm File" button.
- Apply Feature Weights: Use this button to test the classification accuracy of the feature weights currently stored in the program. The classification results will appear in the Details Pane.
- Write *.prm File: Use this button to save the parameter file fragment with the name suggested at the top of this button. This fragment can be loaded into BCI2000 for online testing of the feature weights.

10.11.2.2 Parameters Pane

The Parameters Pane shown in Fig. 10.25 contains all the parameters needed to generate feature weights by using the SWLDA algorithm. These parameters can be loaded using the "Load Ini File" button in the Data Pane. If the parameters are properly configured, the "Generate Feature Weights" button is enabled in the Data Pane.

- Max Model Features: Used to specify the maximum number of features to be used in the SWLDA algorithm. Only a single value can be entered for evaluation. The default value is 60.
- Penter: Used to specify the maximum p-value for a variable to be included in the model. The default value is 0.1. Penter must be less than Premove and 0<Penter<1. Only a single value can be entered for evaluation.
- Premove: Used to specify the maximum p-value for a variable to be removed from the model. The default value is 0.15. Premove must be greater than Penter and 0<Premove<1. Only a single value can be entered for evaluation.
- Spatial Filter: Selects the spatial filter applied to the training data. Select "RAW" or "CAR" from the drop-down menu. "RAW" means that there is no spatial filter applied to the data, whereas "CAR" realizes a common average reference filter using all of the channels contained in the data file, i.e., not just the channels specified in the channel set. The default spatial filter is "RAW."

- Decimation Frequency: Used to specify the temporal decimation frequency of the data in Hz. Only a single value can be entered for evaluation. Set this parameter to the sampling rate used in the data file for no decimation. The lower the Decimation Frequency, the smaller the feature space.
- Channel Set: Used to specify the channel set that will be used to create feature weights. The specified channels must be a subset of the channels contained in the training data file.
- Response Window: Used to specify the beginning and end time (defined in ms) following the stimuli that will be used in the analysis. These two values are automatically converted into samples according to the data's sampling rate. Only

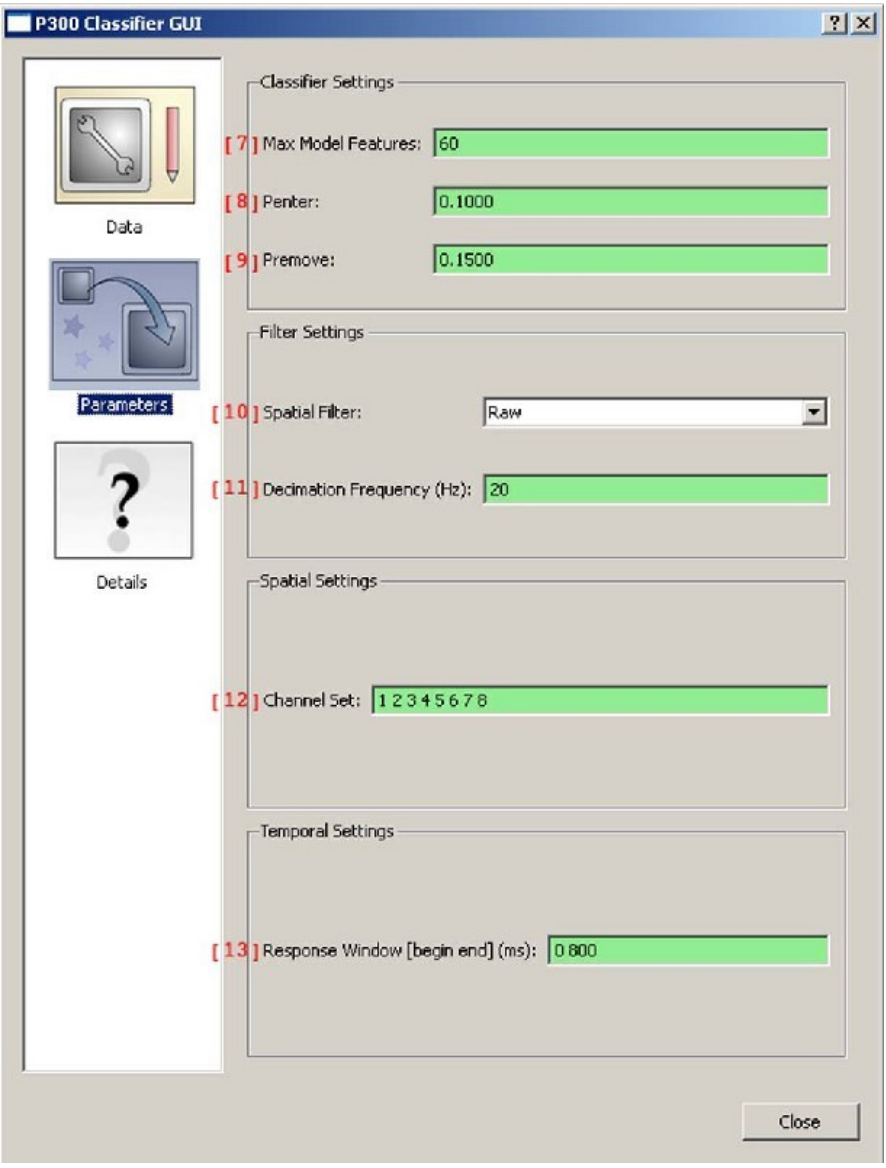
P300 Classifier GUI
Data
Parameters
Details
Classifier Settings
[7] Max Model Features: 60
[8] Penter: 0.1000
[9] Premove: 0.1500
Filter Settings
[10] Spatial Filter: Raw
[11] Decimation Frequency (Hz): 20
Spatial Settings
[12] Channel Set: 1 2 3 4 5 6 7 8
Temporal Settings
[13] Response Window [begin end] (ms): 0 800
Close

Fig. 10.25 The Parameters Pane in the P300 Classifier

a single data window can be entered and will be evaluated. The beginning time
must be less than the end time.

10.11.2.3 Details Pane

The Details Pane (see Fig. 10.26) displays information about the selected BCI2000
training data files and the classification results.

- Sampling Rate: Displays the sampling rate of the training data files in Hz.
- Number of Channels: Displays the total number of channels contained in the training data files.
- Classifier: Displays the classifier algorithm applied to generate the feature
weights. The P300Classifier currently only supports the SWLDA classifier algorithm.
- Application: Displays the type of paradigm. Currently, “P3SpellerTask” and “StimulusPresentationTask” are supported.
- Interpret Mode: Displays the interpretation mode used in the paradigm. The mode can be either “Copy Mode” or “Online Free Mode.”
- Duration: Displays the duration of all training data files in seconds.

The text display shows the classification results for the training and testing data
files.

10.11.3 Reference

The P300Classifier trains and tests a linear classifier (SWLDA) to detect evoked
potentials in brain signals. Classifier training consists of the following steps:

- Load BCI2000 data files.
- Get P300 responses.
- Generate feature weights for a linear, model using SWLDA.
- Apply linear classifier to get scores.
- Interpret scores according to the given application.

The testing consists of the same steps, except that the P300 Classifier will use the linear model derived using the training dataset. These steps are described in more
detail below.

- Step 1: Load BCI2000 Data Files. The first step to using the P300Classifier is to load training and testing data files. These BCI2000 data files are checked for
compatibility and consistency. If all training data files are valid, then the “Gener-
ate Feature Weights” button is enabled and each file is colored with light green.

Otherwise, the “Generate Feature Weights” button is not enabled, and each file
is colored either with yellow or pink. Thus, green, yellow, and pink colors mean
that the respective file is valid, may be valid but there is a mismatch with another
file, or is invalid, respectively.

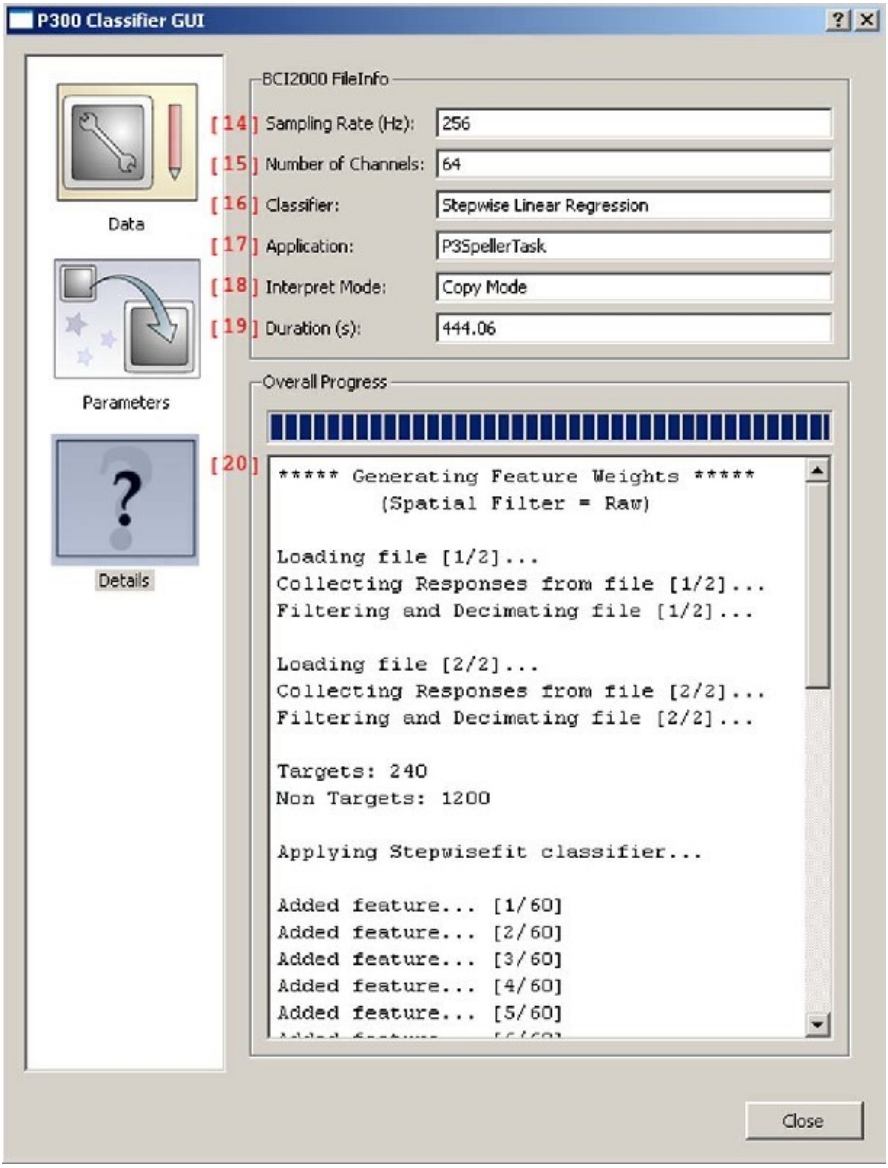

Fig. 10.26 The Details Pane in the P300 Classifier

- Step 2: Get P300 Responses. Signals, states, and parameters are extracted from BCI2000 training and testing data files. The features used for classification are then extracted from the brain signals using the “Response Window” and “Channel Set” specified in the Parameters Pane. These signals are then filtered and downsampled. The filter employed here is a Moving Average (MA) Filter implemented as “Direct form II Transposed.” The MA filter belongs to the finite impulse response (FIR) filter category and works as a low pass filter to remove high frequency components of the signal.
- Step 3: Generate Feature Weights for a Linear Model Using Stepwise Linear Discriminant Analysis (SWLDA). The SWLDA algorithm derives a linear model that relates a set of input features (i.e., filtered brain response) to output labels (i.e., whether or not a P300 response is expected in that brain response) using multiple linear regressions and iterative statistical procedures. Thus, this procedure selects only those brain signal features that are important for distinguishing responses with from responses without P300 responses.
- Step 4: Apply Linear Classifier to Get Score. Scores are computed based on the variables included in the final linear model and the corresponding feature weights.
- Step 5: Interpret Scores. Scores are interpreted according to the given application. The P300 Classifier currently supports either the BCI2000 P300 Speller or StimulusPresentation modules.

10.11.4 Tutorial

Steps to Generate Feature Weights

- Press the “Load Training Data Files” button in the Data Pane.
- From the dialog box, select the desired BCI2000 *.dat file(s) for training. Selected files can be from different sessions of the same paradigm, but must contain consistent parameters. Each training data file is colored according to the color coded scheme explained earlier. Files can only be selected from a single directory; thus, the desired training data files should be organized into the same directory prior to using the P300Classifier.

- Once the Parameters Pane is correctly configured, the “Generate Feature Weights” button is enabled. Press this button to perform the analysis and to generate feature weights. The “Overall Progress” bar displayed in Data and Details panes will indicate the progress of the SWLDA. The classification results will appear in the text window of the “Details” pane. Every time you press the “Generate Feature Weights” button, and the analysis is successfully completed, there will be a new set of feature weights.
- The training procedure can be repeated multiple times with different parameters.

Steps to Generate Feature Weights (continued)

- After training is completed and feature weights are generated, it is recommended to test (cross validate) the feature weights on independent data (i.e., testing data files) before saving the parameter file fragment (*.prm). Additionally, there is a suggested parameter file fragment name that is displayed on the top of “Write *.prm File” button, which can be used to save the parameter file either with the suggested name or the name specified by the investigator.

Steps to Test the SWLDA Classifier

The Data Pane contains the “Apply Feature Weights” button to test the generated feature weights on one or more BCI2000 testing data files. The investigator must follow the next steps for applying feature weights to testing data files:

- Once feature weights are generated, and testing data files exist and have been validated, the “Apply Feature Weights” button is enabled. If no testing data files are loaded, the investigator must press this button to load testing data file(s). One or more BCI2000 *.dat files can be selected from the same directory as a single “test file group” each time the button is pressed. Selected files can be from different sessions of the same paradigm, but must contain consistent parameters. Each testing data file is colored according to the color coded scheme explained earlier. All selected test files should have the same sampling rate and electrode montage as the training data files that were used to generate the current feature weights set.
- After all testing data files are selected, press the “Apply Feature Weights” button to perform the analysis. Results of the classification are displayed in the text window of the Details Pane. The “Overall Progress” bar displayed in the Data and Details panes will indicate the progress of the classification.
- After evaluating the classification results, the *.prm file from the current session can be saved by pressing the “Write *.prm File” button.

10.11.5 Example

In this example, we are interested in computing feature weights from the BCI2000
training data file `eeg3_1.dat` that was created using the P300 Speller paradigm and is provided with the BCI2000 distribution.

First, press the “Load Training Data Files” button. Notice that the training data
file is set up correctly since it is colored in light green. Remember that the classifier
algorithm will be trained using this training data file.

The parameters shown in the Parameters Pane are set by default. For illustration
purposes, we may create an INI file with the following content and then load that
file using the “Load Ini File” button.

```
[Initialization]
maxiter = 60
penter = 0.1000
premove = 0.1500
spatial_filter = 2
decimation_frequency_Hz = 20
channel_set = 1 2 3 4 5 6 7 8
Resp_window_ms = 0 800
```

Once the initial parameters are loaded and properly set up, the “Generate Feature Weights” button is enabled, and each one of the parameter fields is colored in light green. The investigator can change any of the parameter fields at any time. However, if the given parameter is invalid, the corresponding parameter field will turn pink.

Once the parameters are properly configured, the investigator may generate feature weights by pressing the “Generate Feature Weights” button. Details of the training data file and progress of the classification are displayed in the Details Pane. Once the classifier has been trained with the BCI2000 training data file, the next step is to test the derived feature weights with the BCI2000 testing data file `eeg3_2.dat`. By pressing the “Load Testing Data Files” button, this file is loaded into the P300 Classifier program. Notice that the testing data file is set up correctly since it is colored in light green. Because the testing data file is valid, the “Apply Feature Weights” button is enabled. Press the “Apply Feature Weights” button. Details of the training data file (no testing data file) and progress of the classification are displayed in the Details Pane. You can now write a parameter file fragment *.prm with the name suggested in the “Write *.prm File” field by pressing the “Write *.prm File” button.

This parameter file fragment can be imported into BCI2000 for online testing of the feature weights. Remark: every time the investigator changes any of the parameters in the Parameters Pane, the “Apply Feature Weights” button is disabled. To enable it, the investigator must generate new feature weights.

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Chapter 11
Contributed Modules

Any BCI2000 distribution consists of a core and a contribution part. Core components (i.e., modules, or filters) are maintained by the BCI2000 team. We make every attempt to optimize the quality of these components and their documentation. Contributions are usually components that have been created by the BCI2000 community. Because we often cannot replicate the environment that is necessary for execution of these components (this is true particularly for contributed Source modules that make use of other data acquisition devices), we cannot enforce the same level of quality as for the core components. The following sections describe these contributions.

11.1 Source Modules

11.1.1 Amp Server Pro

The AmpServerProADC component supports devices by Electrical Geodesics Incorporated (EGI) by implementing the client side of EGI's TCP/IP-based Amp Server Pro (ASP) protocol. Thus, it may be used to interface BCI2000 with an EGI amplifier managed by an ASP server.

11.1.1.1 Authors

Joshua Fialkoff, Wadsworth Center, New York State Department of Health, 2008.

11.1.1.2 Using the Amp Server Pro Source Module

Amp Server Pro is capable of working with many amplifiers concurrently. To begin

using Amp Server Pro with BCI2000, ensure that at least one amplifier is connected

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to the server. If no amplifier is connected, the Amp Server software emulates an
amplifier. If you choose to use the emulated amplifier, you should expect to see a
smooth sine wave signal for all channels. To start the amp server, simply navigate
to the Amp Server Pro directory and double click the file named `Amp Server`.

11.1.1.3 Compiling the Amp Server Pro Source Module

Because the Amp Server Pro Source Module is a contributed module, you either
need to download the binary distribution for the contributed components, or must
compile the module from the source code before it can be used. To compile the Amp
Server Pro module, you need Borland C++ Builder v6.0 or later. To proceed, please
follow the instructions below:

1. Navigate to `BCI2000/src/contrib/SignalSource/AmpServerPro`.
2. Double click `AmpServerPro.bpr` to open the `Amp Server Pro project file` in the Borland C++ Builder.
3. From the file menu click Project → Make AmpServerPro.

11.1.1.4 Parameters

AmplifierID Amp Server Pro is capable of managing many amplifiers concurrently. BCI2000 operates with one of these amplifiers. If only a single amplifier
is connected, you may enter the value “auto” and allow BCI2000 to automatically
determine the Amplifier ID. If multiple amplifiers are connected, you must enter a
valid ID from 0 to N − 1 where N is the number of amplifiers connected.

CommandPort The port number used for command layer communication. Unless
you have explicitly set the port number via Amp Server’s configuration, the default
of 9,877 should be correct.

NotificationPort The port number used for notification layer communication. Unless you have explicitly set the port number via Amp Server’s configuration, the
default of 9,878 should be correct.

ServerIP The IP address of the computer running the Amp Server software (e.g.,
192.168.0.3).

StreamPort The port number of the port used for data streaming. Unless you have

explicitly set the port number via Amp Server’s configuration, the default of 9,879
should be correct.

11.1.1.5 States

None.

11.1.2 BioRadio

This component supports the BioRadio150 EEG amplifier produced by Cleveland
Medical Devices.

11.1.2.1 Authors

Yvan Pearson-Lecours.

11.1.2.2 Installation

Make sure that the `BioRadio150DLL.dll` file is available in the directory that contains the BioRadio Source module.

11.1.2.3 Parameters

COMPort BioRadio150 COM port. Zero sets the port to AUTO, and a number between one and fifteen sets it to the corresponding COM port (e.g., 1 sets to
COM1, 2 to COM2, etc.).
ConfigPath Absolute path to the BioRadio150 configuration file.
VoltageRange BioRadio150 Voltage Range:

- 7=±100 mV,
- 6=±450 mV,
- 5=±25 mV,
- 4=±412 mV,
- 3=±6mV,
- 2=±3mV,
- 1=±1.5 mV,
- 0=±750 µV.

11.1.2.4 States

None.

11.1.3 BioSemi 2

This Source module supports acquisition from Biosemi devices.

11.1.3.1 Authors

Samuel A. Inverso (samuel.inverso@gmail.com), Yang Zhen, Maria Laura Blefari, Jeremy Hill and Gerwin Schalk.

11.1.3.2 Installation

Copy the `Labview_DLL.dll` to the prog directory for the module to work.

11.1.3.3 Parameters

As of version 2.0 (svn revision 2189), the old parameters PostFixTriggers and TriggerScaleMultiplier have been removed. The functionality of the former is replaced by TriggerChList and the latter can be simulated by setting the corresponding elements of SourceChGain accordingly.

AIBChList A list of indices (each in the range 1 through 32 inclusive) that indicate which Analog Input Box channels are to be acquired. By default, none are acquired. AIB channels are postfixed immediately following the EEG channels.

EEGChlist A list of (one-based) indices to the EEG channels to be acquired. If there are n indices in this list, then the first n channels will be EEG channels.

TriggerChList The old PostfixTriggers parameter has been replaced by this parameter, which gives a list of indices (each in the range 1 through 16 inclusive) indicating which one-bit trigger channels to postfix after the EEG and AIB channels. By default, all 16 are postfixed.

11.1.3.4 States

BatteryLow Set to 1 when hardware reports low battery state.

MK2 Set to 1 when connected to an MK2.

MODE The mode corresponding to the one on the front of the Biosemi box.

11.1.3.5 Known Issues

Pressing Set Config more than once per BCI2000 launch currently (revision 2190) results in unstable amp behavior.

11.1.4 Measurement Computing

The DAS_ADC component handles A/D boards from Measurement Computing (previously called ComputerBoards).

This ADC has been tested and proven to work on the following boards as displayed by the InstaCal program:

DEMO-BOARD
PC-CARD-DAS16/16
PCM-DAS16S/16
CIO-DAS1402/16
PCIM-1602/16

11.1.4.1 Authors

Jürgen Mellinger (juergen.mellinger@uni-tuebingen.de).

11.1.4.2 Installation

The DAS source module uses Measurement Computing's system wide driver and configuration files. If there is an error message saying that loading the DLL failed, you need to download and install a recent version of InstaCal from http://www.measurementcomputing.com (free of charge), and then use it to configure your board.

For the source module to work properly, you need to delete any files named `cbw32.dll` and `cb.cfg` from the directory that contains the Source module. It is also a good idea to delete all other files called `cbw32.dll` and `cb.cfg`, except the ones located in the directory where Measurement Computing's `InstaCal.exe` resides (usually `C:/mmc` or `C:/Program Files/mmc`).

11.1.4.3 Parameters

ADRange A/D input range in Volts, e.g., −5 5, or 0 10. Only certain values are supported, depending on the utilized board.
BoardNumber The A/D Board number as displayed by the InstaCal program.

11.1.4.4 States

None.

11.1.5 Data Translation Boards

The DTADC component supports analog/digital conversion boards by Data Translation.

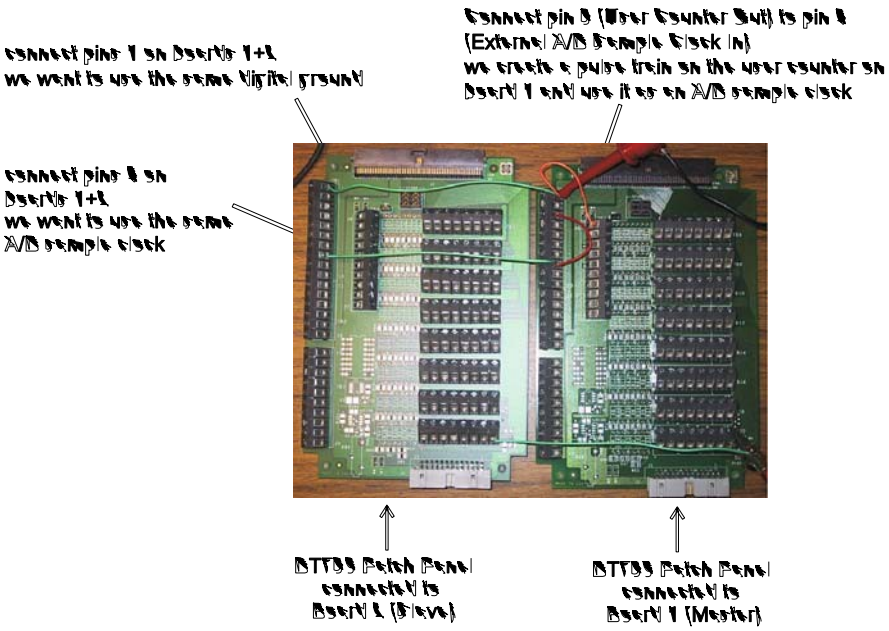
connect pin 1 on board 1+2
we want to use the same digital ground
connect pin 9 (User Counter Out) to pin 1
(External A/D Sample Clock In)
we create a pulse train on the user counter on
board 1 and use it as an A/D sample clock
connect pin 1 on
board 1+2
we want to use the same
A/D sample clock
DT700 Patch Panel
connected to
Board 2 (Slave)
DT700 Patch Panel
connected to
Board 1 (Master)

Fig. 11.1 Photograph of DT730 patch panels with labeled connections

11.1.5.1 Authors

Gerwin Schalk & Dennis McFarland.

11.1.5.2 Installation

The DTADC supports multiple connected boards. To connect multiple boards, and
thus connect BCI2000 systems with up to 128 channels:

- Buy two DT3003 boards and two DT730 patch panels.
- Make the three required connections as shown in Fig. 11.1.
- In BCI2000, set BoardName to the name of board 1, BoardName2 to the name of board 2, SoftwareCh to the total number of channels to be acquired, SoftwareChBoard1 to the number of channels to be acquired from board 1, and SoftwareChBoard2 to the number of channels to be acquired from board 2.
- (SoftwareChBoard1 + SoftwareChBoard2 has to equal SoftwareCh; SoftwareChBoard2 has to be smaller than SoftwareChBoard1).

11.1.5.3 Parameters

BoardName The name of the AD board.

BoardName2 The name of the second AD board, or ‘none’ if there is no second board present.
SoftwareChBoard1 The number of channels for board 1. Ignored in case of a single board.
SoftwareChBoard2 The number of channels for board 2. Ignored in case of a single board.

11.1.5.4 States

None.

11.1.6 Micromed

This module can be used to read data sent over TCP/IP from a Micromed acquisition unit running SystemPLUS Rev. 1.02.1056.

The BCI source module that receives the data from the acquisition is the server, so it must be in listening mode before the acquisition unit starts to save data (data is sent only during recording). Micromed sends 64 data packets per second for SD, 32 for LTM. The connection is reset if the computer running BCI2000 is too slow to read all packets. This happens gracefully in version 2.0. Make sure you have SystemPlus 1.02.1091 or higher. In this version, Micromed also gracefully closes the TCP/IP connection at BCI2000 errors.

A packet of data is structured in two sections. The first section is the header and the second is information data. The first packet sent from the client is the header of an EEG Micromed trace and is read for condition checking. If a note is added in SystemPLUS, it is sent as a note packet to the Source module. If a digital trigger is sent, the trigger code is sent to the Source module in two ways: the complete code and a bitmasked code. This makes it possible to send information on a condition and other information for offline analysis. The header packet and the data packets are in the same format as in a Micromed trace file. The note packet sends the complete note buffer, and is written in a textfile with the Micromed Sample Number.

11.1.6.1 Authors

Erik J. Aarnoutse, Rudolf Magnus Institute, UMC Dept. Psychiatry, Utrecht, The Netherlands, May 19, 2006.

11.1.6.2 Installation

To activate data transfer via TCP, it is necessary to add 3 registry keys on the acquisition unit under `HKEY_CURRENT_USER/Software/VB and VBA Program Settings/Brain Quick - System 98/EEG_Settings`:

1. `tcpSendAcq` is a string type key which must be set to `"1"` to activate data transfer via TCP, and to `"0"` to deactivate it.
2. `tcpServerName` is a string type key that represents the IP address of the computer to receive EEG data.
3. `tcpPortNumber` is a string type key that represents the port number used (e.g., `"5000"`).

11.1.6.3 Parameters

ConditionMask Bitmask. Digital trigger code AND Condition Mask equals conditions without extra information. When not used, set to 0xFF.
NotchFilter Power line notch filter.

- 0: disabled,
- 1: at 50 Hz,
- 2: at 60 Hz.

PacketRate Number of TCP/IP packets per second: 32 for LTM, 64 for SD.
Priority CPU Priority. Default = 1, set higher if the CPU load is too heavy.
SampleBlockSize The number of samples transmitted at a time in the BCI2000
system. If SampleBlockSize is a multiple of SamplingRate/64, data packets are
merged. This way the BCI system can run on less than 64 sampleblocks per second, which saves CPU power.
SamplingRate The sampling rate set by the acquisition unit.
ServerAddress Address and port of the Micromed BCI Server. The port number can be set in the acquisition unit by changing the registry setting `tcpPortNumber`.
SignalType Numeric type of output signal:

- 0: int16,
- 3: int32.

Other values are not allowed. Use 0 for Micromeds 16 bit mode, 3 for 22 bit mode: only the lower 22 bits are used, but data packets are filled with 32 bit integers.
SourceCh The number of digitized and stored channels must match the number of channels in the acquisition unit.

11.1.6.4 States

None.

11.1.7 Modular EEG

This component supports devices built on the ModularEEG concept. The ModularEEG is a GPL-licensed EEG amplifier designed by Joerg Hansmann. The

schematics, PCBs and design-documents were released to the OpenEEG – community in 2002. The ModularEEG is a low-cost EEG system that consists of a microcontroller-based digitizer board and one, two or three analog boards. Each analog board can capture two EEG signals. Thus, the Modular EEG can transmit two, four or six channels of EEG data. The transmission to the host PC or PDA is done via serial RS232 connection. USB converters can be used, and common baud rates are 56,700 or 115,200 bits per second. Be aware that the isolation-barrier for user safety is only 5 kV, which does not meet the criteria for a medical device. Thus, the ModularEEG may not be used for clinical applications. For details and filter specifications please refer to the design documentation (available at http://openeeg.sourceforge.net/doc/modeeg/modeeg_design.html).

The ModularEEG has a 10bit A/D converter and transmits EEG channel data in high byte/low byte format. The gain settings can be adjusted with potentiometers on the analog boards. A 14 Hz 250 µV calibration signal is provided by the digital unit. When calibration is set to ±250 µV, the value 0 corresponds to −250 µV and the value 1,024 corresponds to 250 µV. BCI2000 Signal Processing or any offline analysis routine can derive, as with any other BCI2000 Source module, sample values in µV by subtracting, from each stored sample, SourceChOffset, and multiplying it with SourceChGain for each channel.

11.1.7.1 Authors

- Christoph Veigl, FORTEC-Institute, Technical University Vienna, Austria.
- Gerwin Schalk, Brain–Computer Interface Research and Development Program, Wadsworth Center, New York State Department of Health.

11.1.7.2 Installation

11.1.7.3 Parameters

ComPort Number of the serial port the ModularEEG is connected to.
Protocol Transmission Protocol. There are currently three different protocols for data transmission from or to the EEG device.

- The oldest and most compatible protocol is called P2. It transmits all six channels (even in case there are only two connected) and uses unidirectional communication to the host computer. The P2 protocol is compatible to other EEG applications like “Electric Guru.” A P2-packet consists of 17 bytes.
- P3 is a newer, more compact format. A six-channel data packet has 11 bytes, and the transmission of only four or two channels is possible. There are two firmware versions that are currently in experimental stage. The corresponding protocols are bi-directional and make it possible to send command frames to the ModularEEG.

SampleBlockSize Samples per digitized block.
SamplingRate The sampling rate for the EEG data. Currently, this is fixed to 256 Hz. New firmware versions will support adjustments of the sampling rate.
SimulateEEG When this option is selected, sine waves are generated instead of using real time EEG data. The amplitude and frequency of the sine waves can be adjusted by moving the mouse.
SourceCh The number of channels (2, 4, or 6).

11.1.7.4 States

None.

11.1.8 National Instruments

This Source module supports data acquisition from National Instruments analog/digital (A/D) boards. It was tested using National Instruments' 6.9.x drivers.
It will not work with the newer MX drivers.

11.1.8.1 Authors

Gerwin Schalk, Wadsworth Center, NYSDOH.

11.1.8.2 Installation

11.1.8.3 Parameters

BoardNumber The NI-ADC board's device number.

11.1.8.4 States

None.

11.1.9 National Instruments MX

This NIDAQ_MX Source module supports data acquisition from National Instruments analog/digital (A/D) boards using MX driver version 8.5 or later. The driver
also supports some traditional NIDAQ (legacy) boards; please refer to the official NI documentation for the complete list of supported boards (NI DAQMX 8.5 readme).

The BCI2000-compatible Source module (`NIDAQmx.exe`) can be used instead of any other Source module. It has been tested with DAQPad 6015 USB. In addition to standard parameters (i.e., SampleBlockSize, SamplingRate, SourceCh), this BETA driver is limited to acquiring 16 channels and that the terminal configuration is fixed to “Not Referenced Single Ended” on a bipolar range of ±5 V .
These settings may be changed at compilation time, and all the config instructions
are placed in the `ADConfig()` function. Please refer to your hardware manual for
supported settings.

11.1.9.1 Authors

Giulio Pasquariello, Gaetano Gargiulo, ©2008 DIET Biomedical unit, University of Naples “Federico II”.

11.1.9.2 Installation

Include the `nidaqmx.lib` file in the project. This library file has already been converted from OMF to COFF using the omf2coff DOS utility contained in the Borland C Builder directory and is included in the ZIP file; the original NIDAQmx library is also included, and has been renamed to `NIDAQmx_orig.lib`.

11.1.9.3 Parameters

BoardNumber The NI-ADC board’s device number.

11.1.9.4 States

None.

11.1.10 Neuroscan

The NeuroscanADC component implements the client side of the TCP/IP-based Neuroscan Acquire protocol. Thus, it may be used to interface BCI2000 with Neuroscan EEG systems.

NuAmps/SynAmps are EEG recording systems from Neuroscan, Inc., that are widely used in clinical settings. This section describes this support that consists of
two components: A BCI2000-compatible Source module (`Neuroscan.exe`) and a

command-line tool (neurogetparams). These components are described below and
have been tested with Neuroscan Acquire version 4.3.1.

11.1.10.1 Using the NeuroscanADC Module

The BCI2000-compatible Source module Neuroscan.exe can be used instead of any other source module. In addition to standard parameters (i.e., SampleBlock-Size, SamplingRate, SourceCh), it only requests one Neuroscan-specific parameter (ServerAddress) that defines the IP address (or host name) and the port number of the Acquire server. An example for an appropriate definition is localhost:3999.
Before starting BCI2000, you need to start Acquire,clickontheS symbol in the top right corner (to enable the server) and start the server on any port. Please note that by default, Acquire suggests port 4000, which is a port used by BCI2000. You might use port 3999 instead. Once the server is running, you can start BCI2000. It is imperative that certain parameters (e.g., the number of channels) in BCI2000 match the settings in Acquire. You can read these settings from Acquire using the command line tool described in the following section. This command line tool can create a parameter file fragment that needs to be loaded on top of an existing parameter file every time a setting in Acquire is changed.

11.1.10.2 Authors

Gerwin Schalk, Wadsworth Center, New York State Department of Health, 2004.

11.1.10.3 Parameters

ServerAddress Address and port of the Neuroscan Acquire server, given in `address:port` format.

11.1.10.4 States

NeuroscanEvent1 An 8-bit state that encodes event information as sent over the Neuroscan Acquire protocol.

11.1.10.5 Neurogetparams Command Line Tool

This command line tool reads system settings from the Neuroscan Acquire server, displays them on a screen and creates a BCI2000 parameter file fragment if desired. It can be used as follows: `neurogetparams -address localhost:3999 -paramfile test.prm`. (TheAcquire server has to be enabled before using

this tool.) Once BCI2000 is configured correctly, this parameter file fragment needs
to be loaded on top of the existing configuration to make sure that the settings match.
You only need to repeat this procedure if you change settings in Acquire (e.g., such
as the number of channels or the amplification). An example of the output display
for this tool can be seen in Appendix B.

11.1.11 BrainAmp Systems

A Source module that interfaces BCI2000 with BrainAmp EEG systems (Brain-Products, Inc.) using the TCP/IP-based BrainAmp RDA interface.

11.1.11.1 Authors

Jürgen Mellinger (juergen.mellinger@uni-tuebingen.de), Thomas Schreiner (thomas.schreiner@tuebingen.mpg.de), Jeremy Hill.

11.1.11.2 Parameters

HostName IP address or name of the host to connect to, typically localhost.
SampleBlockSize The number of samples transmitted at a time. The VisionRecorder appears to send one block every 40 ms, so SampleBlockSize should
match SamplingRate × 40 ms.
SamplingRate The sampling rate as configured in the VisionRecorder program.
SourceCh The number of digitized and stored channels. This must match the setting in the VisionRecorder program, increased by 1 to account for an additional
channel to hold marker information.

11.1.11.3 States

None.

11.1.11.4 getparams Tool

`getparams` is a command line utility that makes it possible to obtain appropriate
Source module parameters from a host running BrainAmp's VisionRecorder.

On the target host, start the VisionRecorder program, check that RDA is enabled
under Configuration → Preferences, and click the monitor (eye) button before running `getparams` with the host's IP address as the only parameter (when omitted,
this defaults to localhost).

To direct the output into a file that can later be loaded into the Operator module's
configuration dialog, append a redirection to the command:

```
getparams localhost > myparamfile.prm
```

11.1.12 Tucker-Davis Technologies

The TDTclient Source module interfaces BCI2000 with a Tucker-Davis Technologies (TDT) RX5 Pentusa system or RZ2 System. The TDT systems are capable of multi-channel (up to 64, or higher), high data transfer rates (more than 1 GB/s) allowing for high density EEG, ECoG, or even single-unit recordings. The system is highly configurable, allowing the user to use digital filtering and complex analysis on the hardware.

Currently, the TDTclient supports the following system configuration:

- TDT Pentusa/RX5 OR.
- TDT RZ2.
- GBIT or Optibit.
- ActiveX libraries installed (to install from source).

The obsolete Medusa system is not currently supported.

11.1.12.1 Authors

J. Adam Wilson (jadamwilson2@gmail.com), Department of Neurosurgery, University of Cincinnati.

11.1.12.2 Installation

The most current TDT drivers should be downloaded and installed from www.tdt.com. Also, make sure that the microcode on the hardware is updated to the latest version as well, or the TDT source module will not work.

Currently, the TDT ActiveX library must be installed on the local machine in order to use the TDTclient. It can be obtained from www.tdt.com, and it requires a password to install.

11.1.12.3 Parameters

CircuitPath The Circuit Path is the path to the TDT *.rco or *.rcx file to be used. Several files are included.

- chAcquire64.rco – Up to 64 channels from the RX5 system; requires a five processor system.
- chAcquire16.rco – Up to 16 channels from the RX5 system; requires a two processor system.
- chAcquire64_RZ2 – Up to 64 channels from the RZ2 system.

An eight-processor RZ2 system exists that should be capable of recording 256 channels. It is currently not supported.

DigitalGain If digital inputs are used on the front panel, they must be converted from a digital value (0 or 1) to a floating-point value with this scale factor.

FrontPanelList A list of front panel components to collect. The RZ2 system provides eight analog inputs and eight digital inputs which can be recorded as extra channels into BCI2000. To collect all eight analog channels, enter `1 2 3 4 5 6 7 8` for this value; to collect just digital channels, enter `9 1 0 1 1 1 2 1 3 1 4 15 16`. Any combination of 1–16 is valid. Note: The number of values listed here plus NumEEGchannels must add to the value entered in the SourceCh parameter!

FrontPanelGain Analog inputs recorded from the front panel will have a different gain than those recorded on the EEG preamps, and need a different gain value to be recorded properly.

HPFfreq The corner frequency of the digital high-pass filter in the circuit. This can be set to 0 to not be used, but be aware that the Medusa pre-amps have an analog high-pass filter at 1.5 Hz built in.

LPFfreq The corner frequency of the digital low-pass filter. This can be set to any value, but it is recommended that the highest value used is at half of the sampling frequency (i.e., 256 for a sample rate of 512).

NumEEGchannels The number of EEG channels to acquire. These are channels recorded from the preamp. NumEEGchannels plus the number of entries in FrontPanelList must add to SourceCh.

notchBW This is the bandwidth of the 60 Hz notch filter. If set at 10, the bandstop filter will have corner frequencies of 55 and 65 Hz.

nProcessors The number of processors on the TDT system. This value must correspond to the rco file used in CircuitPath. For example, the `chAcquire64_RZ2.rcx` and `chAcquire16.rco` should have nProcessors set to 2, while `chAcquire64.rco` should use 5.

SampleRate The sampling rate of the system. Use the TDTsampleRate program to calculate the value to enter here. The TDT has a fixed rate of 24,414.0625 Hz, so the requested sample rate must be some integer fraction of this value. For example, a sample rate of 512 Hz is not possible, because it is impossible to find an integer that will divide 24,414.0625 to get 512. The closest rate to 512 Hz that can be used is 519.448, because 24,414.0625/519.448 = 47, which corresponds to the down-sampling factor.

TDTgain The amount of gain to add to the signals acquired from the amplifier. To convert to µV, this should be 1,000,000, unless the EEG pre-amplifier is used, in which case this should be 50,000, since the pre-amp adds a 20x gain.

11.1.12.4 States

None.

11.1.13 TMS Refa and Porti Systems

A Source module that interfaces BCI2000 to TMS Refa and Porti systems.

11.1.13.1 Authors

M.M. Span, ©RUG University of Groningen.

11.1.13.2 Parameters

The standard Source module parameters are used.

11.1.13.3 States

None.

11.1.14 BrainProducts V-Amp

The vAmpADC filter acquires data from up to four V-Amp or FirstAmp EEG amplifiers. The V-Amp is an amplifier/digitizer combination from Brain Products. Support for this device in BCI2000 consists of a BCI2000-compatible Source module (`vAmpSource.exe`).

11.1.14.1 Authors

J. Adam Wilson, University of Wisconsin–Madison & The Wadsworth Center, Albany, NY.

11.1.14.2 Hardware

The V-Amp consists of 16 independent 24-bit A/D converters that can sample at up
to 2 kHz per channel (16 channels, plus two auxiliary) or 20 kHz per channel (four
channels).

11.1.14.3 Installation

The necessary system drivers are located in the `BCI2000/src/extlib/brainproducts/vamp/` folder. To install the driver, follow these steps:

1. Plug in the V-Amp to a USB port. Windows should recognize it, and start to
   install drivers.
2. Depending on the version of Windows being used, a “Found New Hardware”
   dialog should appear. Do NOT search online for drivers; instead, select Don’t
   Search Online.

3. When it asks you to insert the disc that came with the amplifier, select the option
that allows you to browse for the driver.
4. Navigate to `BCI2000/src/extlib/brainproducts/vamp/`. It should find the driver files, and install the necessary software.
5. For the last step, copy the files `DiBpGmbH.dll` and `FirstAmp.dll` to the `BCI2000/prog/`folder.
6. You should now be able to run the `vAmpSource.exe` module in BCI2000.

11.1.14.4 Parameters

SamplingRate The sample rate of the system. All data are acquired either at
2,000 Hz or 20 kHz, and then decimated to the desired rate. Therefore, only rates
that are integer divisors of the base rates are accepted. In 2,000 Hz mode, the valid rates are:

- 2,000
- 1,000
- 666.6
- 500
- 400
- 333.3
- 285.7
- 250
- 222.22
- 200

In 20 kHz mode, 10 times the above rates are valid. Prior to decimation, a second-order anti-aliasing Butterworth filter with a corner frequency of 0.45 times the sam-
pling rate is applied to the signal. All sampling rates are supported for one or more amplifiers. If you are sampling at high rates and from multiple amplifiers, the CPU may be overloaded depending on the speed of your computer and the BCI2000
configuration. In case you are experiencing problems (e.g., data loss, jerky display, etc.), increase the SampleBlockSize so that you are updating the system less fre-
quently (usually, updating the system 20–30 times per second is sufficient for most
applications), and increase Visualize → VisualizeSourceDecimation. This parame-
ter will decrease the number of samples per second that are actually drawn in the
Source display.

DeviceIDs List of serial numbers (e.g., `70`) of all devices. Serial numbers of found devices will be listed in the BCI2000 log window. If you have more than one device, this list determines the order of the channels in the data file.

HPFilterCorner A high-pass digital filter for removing DC offsets. This occurs

after data has been read into BCI2000, and before it is stored to disk.

SampleBlockSize Samples per channel per digitized block. Together with the sampling rate, this parameter determines how often per second data are collected, processed, and feedback is updated. For example, at 600 Hz sampling and a SampleBlockSize of 20 samples, the system will operate at 30 Hz. Typical values are 16 to 64 samples.

BlockSize of 20, the system (e.g., source signal display, signal processing, and stimulus presentation) is updated 30 times per second.

SourceChDevices The number of channels acquired from each device. If there is only one device, this parameter has to equal SourceCh. For example, '16 8' will acquire channels from the first device listed under DeviceIDs, and eight channels from the second device listed under DeviceIDs. Data acquisition always starts at channel 1. The sum of all channels (e.g., 24 in this example) has to equal the value of SourceCh. In high-speed mode, this number may not be higher than 5 per device (four channels + digital).

SourceChList The list of channels that should be acquired from each device. The total number of channels listed should correspond to SourceCh. For more than one device, SourceChDevices determines how the SourceChList values are mapped to each device. For example if SourceChDevices = '8 8' and SourceChList = '1 2 3 4 1 3 1 4 1 5 1 6 5 6 7 8 9 1 0 1 1 1 2', then channels 1-4 and 13-16 will be acquired on the first device, and channels 5-12 will be acquired on the second device. These channels will be saved in the data file as 16 contiguous channels. The order of channels does not matter; i.e., '1 2 3 4' is the same as '2 3 1 4'. The channels are always in ascending order on a single device. Channels may not be listed twice on a single device; e.g., entering '1 2 3 4 5 6 7 1' if SourceChDevices = '8' will result in an error. If this parameter is left blank (the default), then all channels are acquired on all devices. For the V-Amp 16, channels 1-16 are EEG channels, 17-18 are Auxiliary channels, and 19 contains the eight digital channels stored in bits.

AcquisitionMode

- If set to analog signal acquisition, the V-Amp records analog signal voltages (default).
- If set to high-speed acquisition, the V-Amp records analog signals at 20 kHz instead of 2,000 Hz.
- If set to Calibration, the signal output is a square wave test signal generated by the V-amp (which can be used to verify correct system calibration).
- If set to Impedance, impedance values are recorded instead of the signal.

This impedance test reports input impedances for each channel in a separate win-
dow. Values are color-coded according to the magnitude (Green for 0–5 kOhm, Or-
ange for 5–30 kOhm, Red for 30–1000 kOhm, Purple for impedances >1 MOhm).
Values are updated in real time. Channels are shown in columns, and devices in
rows.

11.1.14.5 States

None.

11.1.14.6 Data Format and Storage

- The signals are originally recorded from the V-Amp as 32-bit integers, and converted into µV.
- The auxiliary input units are in Volts.
- SourceChOffset is required to be zero for all channels.

Any offline analysis routine can derive (as with any other BCI2000 Source module) sample values in µV by subtracting, from each stored sample, SourceChOffset (i.e., zero), and multiplying it with SourceChGain for each channel. If SignalType is set to `float32`, data samples are stored in units of µV. In this case, SourceChGain should be a list of 1's (because the conversion factor between data samples into µV is 1.0 for each channel). Even when you specify values other than 0 and 1, BCI2000 will produce a consistent data file, i.e., values will be transformed before they are written to the file such that applying SourceChOffset and SourceChGain will reproduce the original values in µV.

11.2 Tools

11.2.1 EEGLabImport

11.2.1.1 Synopsis

EEGLabImport is a plugin for EEGLAB that allows importing data, including the recorded signal and event markers, that is stored in the BCI2000 data format. Data from multiple runs can be concatenated and imported simultaneously, greatly extending and simplifying the analysis of EEG- and ECoG-based data sets. Further information about EEGLAB can be found at: http://sccn.ucsd.edu/eeglab/.

11.2.1.2 Prerequisites

BCI2000import requires Matlab 7.0 or greater and a current version of EEGLAB. Depending on the size of the data sets, a large amount of RAM may also be required, due to resource requirements of Matlab.

11.2.1.3 Installing EEGLabImport

Installation of the plugin is straightforward, but may require compiling the
`load_bcidat` MEX function for your platform.

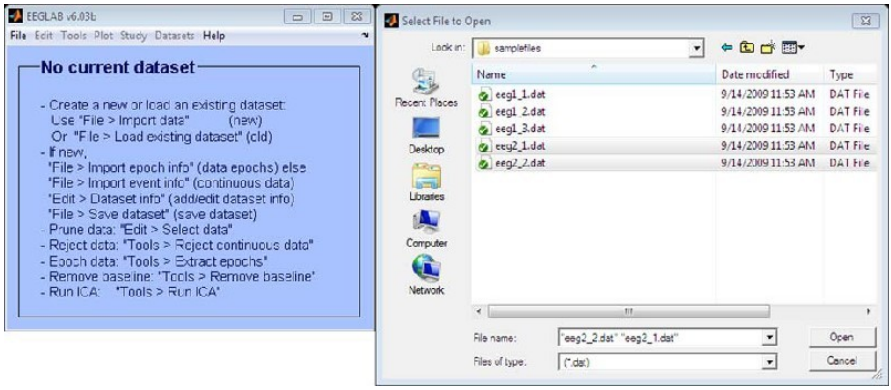
EEGLAB v6.03b
File Edit Tools Plot Study Datasets Help
No current dataset
- Create a new or load an existing dataset:
Use "File > Import data" (new)
Or "File > Load existing dataset" (old)
- If new,
"File > Import epoch info" (data epochs) else
"File > Import event info" (continuous data)
"Edit > Dataset info" (add/edit dataset info)
"File > Save dataset" (save dataset)
- Prune data: "Edit > Select data"
- Reject data: "Tools > Reject continuous data"
- Epoch data: "Tools > Extract epochs"
- Remove baseline: "Tools > Remove baseline"
- Run ICA: "Tools > Run ICA"
Select File to Open
Look in: samplefiles
Recent Places
Desktop
Libraries
Computer
Network
Name
Date modified
Type
eeg1_1.dat 9/14/2009 11:53 AM DAT File
eeg1_2.dat 9/14/2009 11:53 AM DAT File
eeg1_3.dat 9/14/2009 11:53 AM DAT File
eeg2_1.dat 9/14/2009 11:53 AM DAT File
eeg2_2.dat 9/14/2009 11:53 AM DAT File
File name: "eeg2_2.dat" "eeg2_1.dat"
Files of type: (*.dat)
Open
Cancel

Fig. 11.2 The EEGLabImport program. Multiple files have been selected in this example

EEGLabImport

1. If you are using a 32-bit version of Windows, `load_bcidat.mexw32` is likely already compiled for your platform, and can be located in the `BCI2000/tools/mex/` folder. Copy this file to the `BCI2000/tools/EEGLabImport` folder, and skip to 5.
2. If you are using a platform for which a version of `load_bcidat` does not exist in the `/tools/mex` folder, the `load_bcidat` MEX file must be compiled.
3. Open Matlab, and navigate to `BCI2000/src/core/Tools/mex/`. Type `buildmex` at the command line; this will build the BCI2000 MEX functions for your platform.
4. Once the build process is complete, locate the `load_bcidat` file for your platform based on its extension (see the Matlab MEX documentation for more details), and copy it to `BCI2000/tools/EEGLabImport`.
5. Copy the folder `BCI2000/tools/EEGLabImport` to the EEGLab plugin folder, located at `eeglab/plugins`.

When EEGLAB is started, the BCI2000 data plugin will be automatically detected and installed.

11.2.1.4 Using EEGLabImport

Begin a Matlab session, and start EEGLAB by typing `eeglab` at the command prompt. EEGLabImport is detected and added to the menus automatically. Go to
File → Import Data → BCI2000 Data to start the data import program. A file selection dialog is presented, in which multiple BCI2000 data files can be selected (see
Fig. 11.2). The default file extension for BCI2000 data files is *.dat. Select one or
more files from the desired folder, and press Open.

After pressing Open, the program loads the selected data, including the signal,
states, and testing parameters such as the sampling rate. Next, a window will appear

asking which BCI2000 states should be imported as EEGLAB events. Several important and common states will automatically be selected, but it is not required to import these. These events are used to generate signal epochs, which are then used for signal averaging and other analyses. Each event relates to a different experimental event.

Once the desired events are selected, EEGLabImport removes the undesired states, and finishes importing the data into EEGLAB. The final step is to give the dataset a name, and to optionally save the file in the EEGLAB format for future analysis.

11.2.1.5 Tutorial

This tutorial covers some of the basics of using EEGLAB to analyze data from a BCI experiment. The sample data sets used for this are included in the `BCI2000/data/samplefiles` folder. This data was collected during a P300 Speller training session, and EEGLAB will be used to compare the evoked response for the attend and ignore conditions.

Importing BCI2000 Data

1. Open Matlab, and navigate to the EEGLAB folder. Type `eeglab` to start EEGLAB.
2. In EEGLAB, go to File → Import Data → From BCI2000 *.DAT.Navigateto `BCI2000/data/samplefiles/`, and select `eeg2_1.dat` and `eeg2_2.dat`.
3. When EEGLAB asks which BCI events to import, select `StimulusCode`, `StimulusType`, and `StimulusBegin` (Fig. 11.3).
4. When asked, name the dataset P300.

Importing Channel Locations

In order to utilize many of EEGLAB's functions, it needs to know the location of each channel on the head. This is accomplished by loading a channel location file.

Importing Channel Locations

1. In EEGLAB go to Edit → Channel Locations. This brings up the channel location edit window (Fig. 11.4).
2. Press the Read Locations button in the lower-left corner. Navigate to `BCI2000/data/samplefiles/`, and select `eeg64.loc`.
3. A window appears asking for the File Format; select `autodetect`, and press OK.
4. The channel locations are imported, and you can view the information for each electrode.

5. Press the OK button to close the channel edit window.

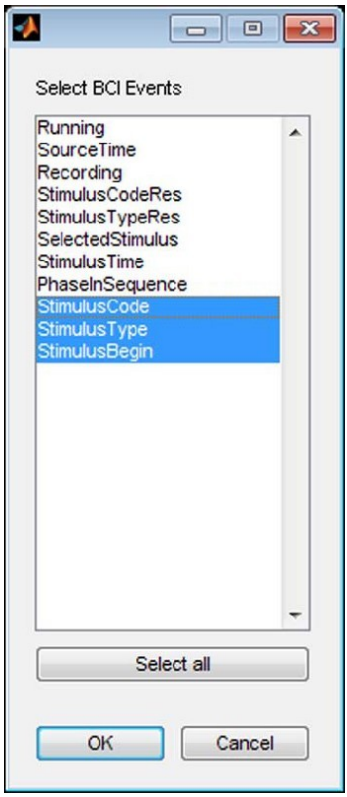

Fig. 11.3 In this example, the states `StimulusCode`, `StimulusType`,and `StimulusBegin` will be imported into EEGLAB

Importing Channel Locations (continued)

6. To verify that the channels are imported correctly, go to Plot → Channel Locations → By name. A plot showing each channel's location is displayed on a simple 2D view of a head.

Epoching Data

The next step is to epoch the data based on one or more events that were imported. The BCI task can be epoched in many ways, but the way it will be done here is by using the StimulusBegin state as the event marker. This BCI2000 state corresponds to the beginning of each flashing letter during the P300 Spelling task, and is therefore suitable to epoch the data for ERP analysis.

Importing Channel Locations

1. In EEGLAB, go to Tools → Extract Epochs (Fig. 11.5).
2. The Time-locking event parameter determines which event should be used to create the epochs. Enter `StimulusBegin` in this field.

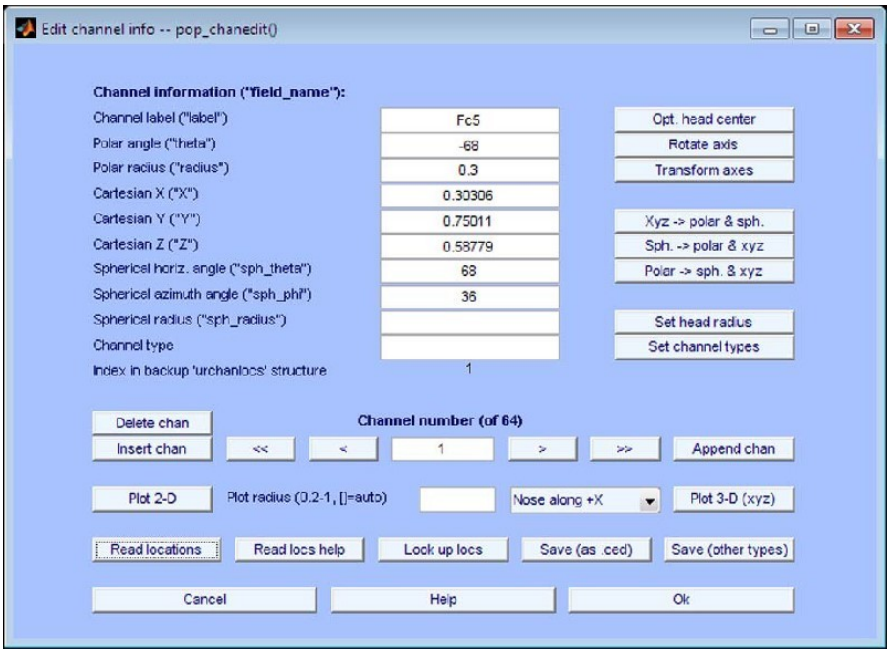

Fig. 11.4 Channel location edit window

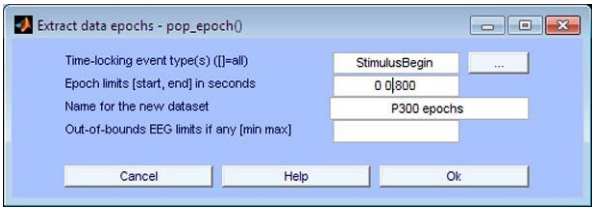

Fig. 11.5 Extracting data epochs

Importing Channel Locations (continued)

3. The Epoch limits parameter determines the time ranges of the data before and after each event. Enter `0 0.800` in this field, to keep the data starting with the flash onset to 800 ms after the flash.
4. In the Name for the new dataset field, enter `P300 Epochs`.
5. Press the OK button to finish.
6. A dialog asks to name the new dataset; enter `P300 Epochs` into the appropriate field.
7. The last dialog asks to remove the baseline from each epoch. Press Ok to remove the baseline from the entire epoch.

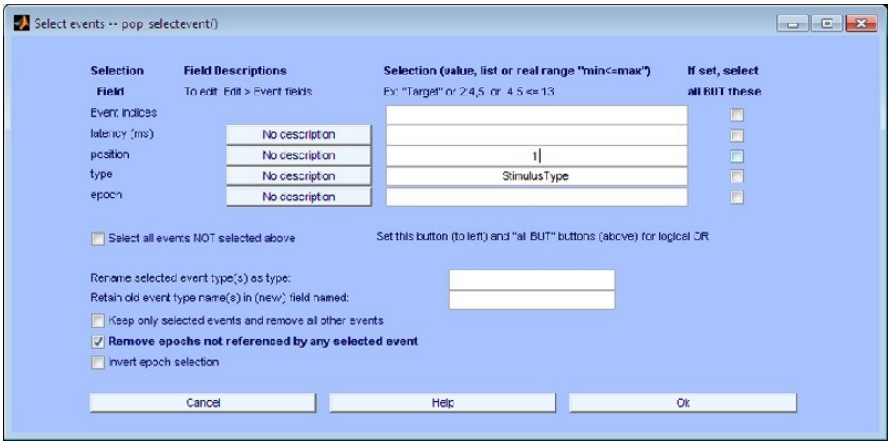

Fig. 11.6 Selecting attended epochs

A new dataset with the name `P300 Epochs` is created and activated. An important note to make here is that EEGLAB does not write over old datasets when operations are performed, but creates an entirely new set. Therefore, the set we just created is given an index of 2; the currently selected dataset can be changed in EEGLAB in the Datasets menu.

Extracting Task-Specific Conditions

During the P300 Spelling calibration test, the user is instructed to pay attention to specific letters while the letter matrix is flashing. The `StimulusType` state and event specifies whether the current flashing letter is the letter that the user should attend to. Therefore, the brain response for the Attend and Ignore conditions can be compared using this event by extracting the appropriate epochs.

Extracting the Attend Condition

1. In EEGLAB, select the Edit → Select Epochs/Events menu, which displays the Select Event dialog (Fig. 11.6).
2. We want to select the epochs in which the `StimulusType` equals 1. Therefore, enter `StimulusType` in the type field, and `1` in the position field.
3. The remaining options should not be changed. Press Ok to continue.
4. A Confirmation dialog is displayed warning that 160 epochs will be removed from the new data set. Press Ok to confirm.
5. A new dataset is created containing only the brain responses to the attended stimuli. A dialog asks what to name the dataset; enter `P300 Attend` into the appropriate field, and press Ok to continue.

Next, the brain signals for the Ignore condition will be extracted in a similar manner.

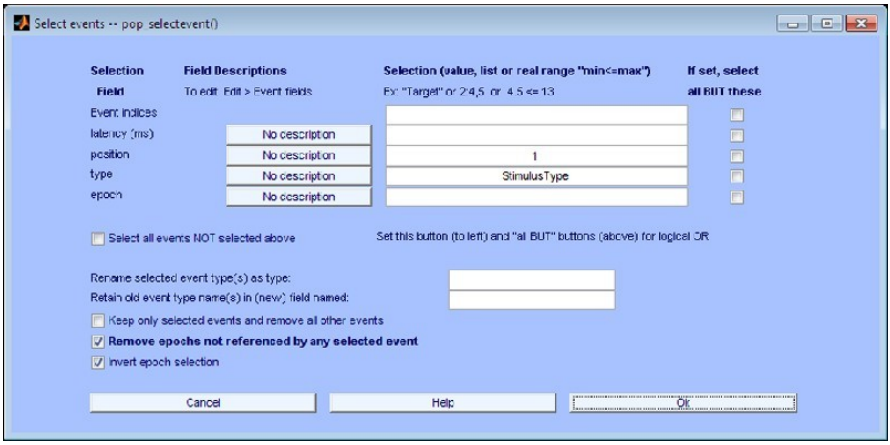

Fig. 11.7 Selecting ignored epochs

Extracting the Ignore Condition

1. First, the epoched dataset must be re-selected. Currently, dataset #3 is likely
   selected in EEGLAB, and this does not contain any “Ignore” data. Therefore, click Datasets → Dataset 2: P300 Epochs to select the correct dataset.
2. In EEGLAB, select the Edit → Select Epochs/Events menu, which displays the Select Event dialog (Fig. 11.7).
3. We want to select the epochs in which the `StimulusType` does not equal 1. Therefore, enter `StimulusType` in the type field, and `1` in the position field.
4. In the lower-left corner, click the box that says Invert epoch selection. This finds all of the epochs for which `StimulusType` equals 1, and selects all others, which corresponds to the Ignore condition. Press Ok to continue.
5. A Confirmation dialog is displayed warning that 40 epochs will be removed from the new data set. Press Ok to confirm.
6. A new dataset is created containing only the brain responses to the ignored
   stimuli. A dialog asks what to name the dataset; enter `P300 Ignore` into the appropriate field, and press Ok to continue.

Plotting ERP Maps

Next, we will plot the brain responses for the Attend condition.

Plotting the ERP Map

1. Select Datasets → Dataset 3: P300 Attend.
2. Select Plot → Channel ERPs → With scalp maps.
3. A dialog window appears with options for plotting the ERPs (Fig. 11.8).
4. For the Plotting time range field, keep the default value of `0 793.75`.

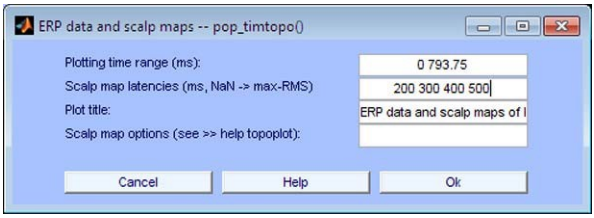

Fig. 11.8 Options for plotting ERPs

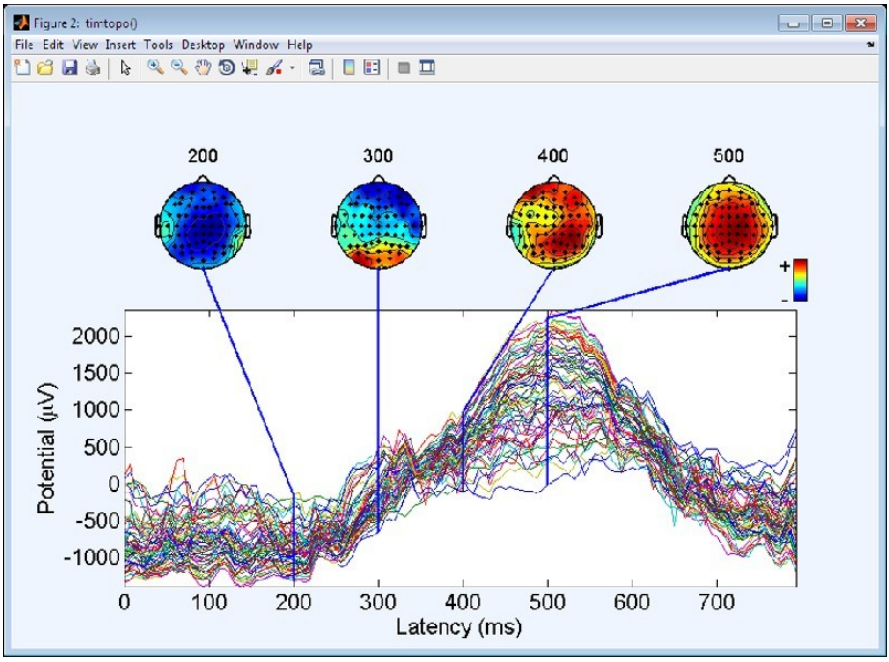

Fig. 11.9 ERP and scalp map for the Attend condition

Plotting the ERP Map (continued)

5. For the Scalp map latencies field, enter `200 300 400 500`. These plot the scalp topographies at these latencies. Alternatively, leave this field blank, and
   EEGLAB will select the latency with the largest response.
6. Press Ok.
7. A plot of the averaged ERP for each channel is shown, along with the scalp maps at each latency (Fig. 11.9).

In Fig. 11.9, we can see that there is a large response centered over the Cz/Pz
electrodes approximately 500 ms after the stimulus, as expected. It is also instructive
to compare the Attend response to the Ignore response. To do so, select Datasets →

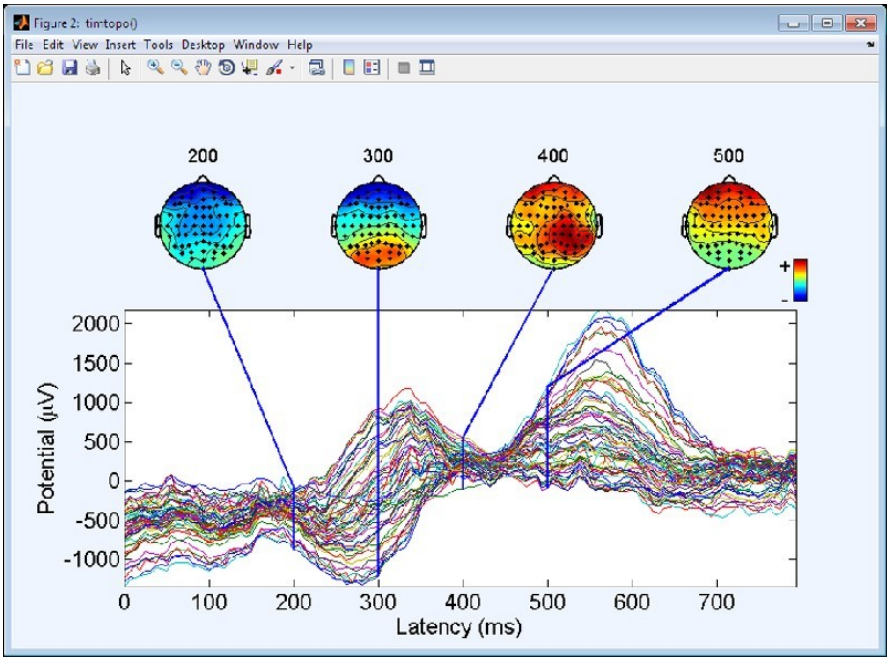

Fig. 11.10 ERP and scalp map for the Ignore condition

Dataset 4: P300 Ignore, and repeat the above steps to plot the ERP for the Ignore
condition (Fig. 11.10).

Comparing ERP Responses

Finally, the ERPs for both conditions will be plotted to determine the locations
and times of the largest differences.

Plotting the ERP Differences

1. Select Plot → Sum/Compare ERPs. The ERP grand average dialog appears (Fig. 11.11).
2. For Datasets to average, enter 3.
3. For Datasets to average and subtract, enter 4. This specifies that the average ERP for dataset 4 should be subtracted from the average ERP for dataset 3.
4. Make sure that the other options are not changed, and press Ok.

A plot of the ERPs at all locations are shown, including the attend (green) and
ignore (blue) conditions, and the difference between them (purple) (Fig. 11.12).

To inspect an individual channel, click on its location in this plot. For example,
click on the Cz axis to display an enlarged plot of the ERPs, as in Fig. 11.13.

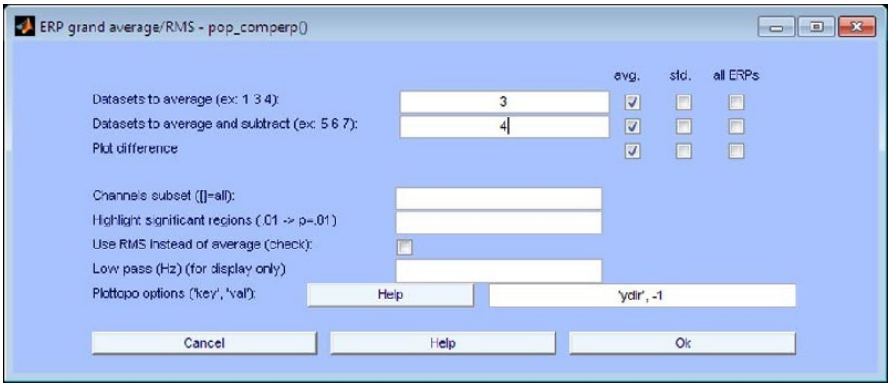

Fig. 11.11 The ERP grand average dialog

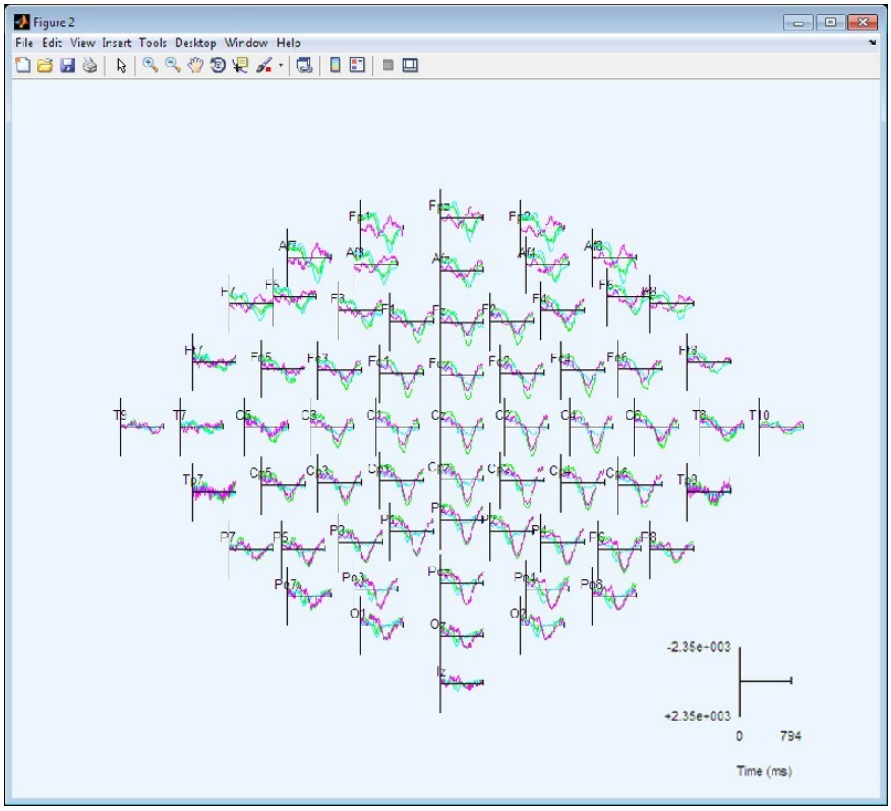

Fig. 11.12 ERPs for the Attend and Ignore conditions, and the difference between the ERPs

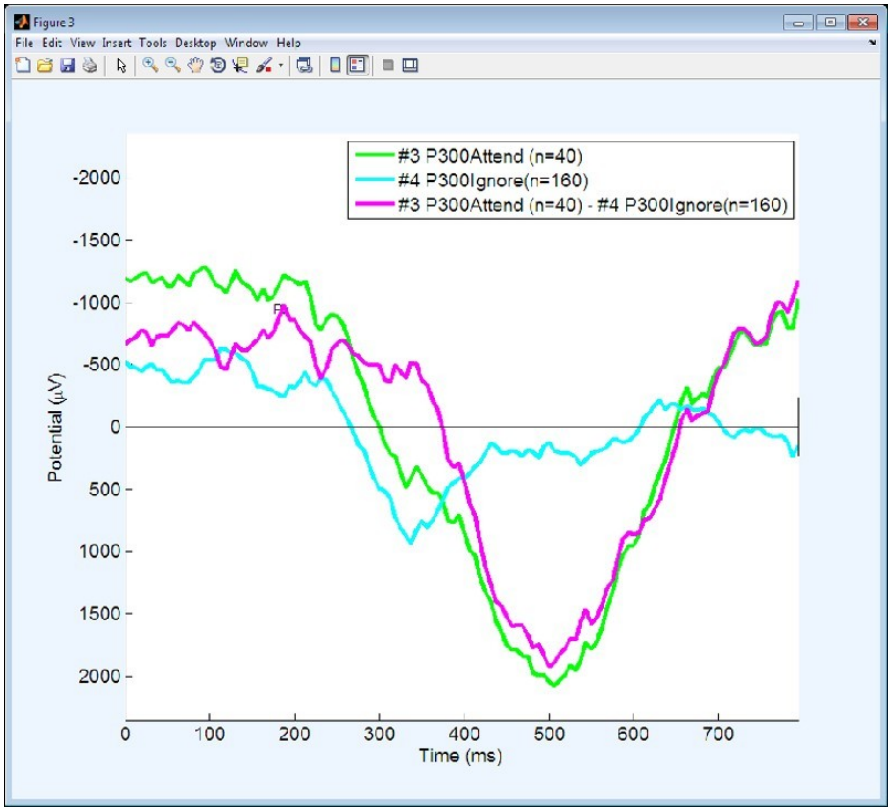

Fig. 11.13 ERPs for the Attend and Ignore conditions, and the difference between the ERPs on channel Cz

11.2.1.6 Further Information

This tutorial aimed at getting you started using EEGLAB for analyzing BCI2000 data. Detailed information on using the EEGLAB software is provided by the EEGLAB tutorial, which is available at the EEGLAB homepage at http://www.sccn.ucsd.edu/eeglab/.

Appendix A
The USBampGetInfo Command Line Tool

The USBampGetInfo tool prints information about the filter capabilities of attached
g.USBamp amplifiers. This information can be used to configure the USBamp-Source.exe module with proper filter settings.

```
****************************************
BCI2000 Information Tool for g.USBamp
****************************************
(C)2004 Gerwin Schalk
     Wadsworth Center
     New York State Department of Health
     Albany, NY, USA
****************************************
Amp found at USB address 1 (S/N: UA-200X.XX.XX)
Printing info for first amp (USB address 1)

Available bandpass filters
==================================
num| hpfr  | lpfreq |  sfr | or | type
==================================
000|  0.10 |    0.0 |   32 |  8 | 1
001|  1.00 |    0.0 |   32 |  8 | 1
002|  2.00 |    0.0 |   32 |  8 | 1
003|  5.00 |    0.0 |   32 |  8 | 1
004|  0.00 |   15.0 |   32 |  8 | 1
005|  0.01 |   15.0 |   32 |  8 | 1
006|  0.10 |   15.0 |   32 |  8 | 1
007|  0.50 |   15.0 |   32 |  8 | 1
008|  2.00 |   15.0 |   32 |  8 | 1
009|  0.10 |    0.0 |   64 |  8 | 1
010|  1.00 |    0.0 |   64 |  8 | 1
011|  2.00 |    0.0 |   64 |  8 | 1
012|  5.00 |    0.0 |   64 |  8 | 1
013|  0.00 |   30.0 |   64 |  8 | 1
014|  0.01 |   30.0 |   64 |  8 | 1
```


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```
015|  0.10 |   30.0 |   64 |  8 | 1
016|  0.50 |   30.0 |   64 |  8 | 1
017|  2.00 |   30.0 |   64 |  8 | 1
018|  0.10 |    0.0 |  128 |  8 | 1
019|  1.00 |    0.0 |  128 |  8 | 1
020|  2.00 |    0.0 |  128 |  8 | 1
021|  5.00 |    0.0 |  128 |  8 | 1
022|  0.00 |   30.0 |  128 |  8 | 1
023|  0.00 |   60.0 |  128 |  8 | 1
024|  0.01 |   30.0 |  128 |  8 | 1
025|  0.01 |   60.0 |  128 |  8 | 1
026|  0.10 |   30.0 |  128 |  8 | 1
027|  0.10 |   60.0 |  128 |  8 | 1
028|  0.50 |   30.0 |  128 |  8 | 1
029|  0.50 |   60.0 |  128 |  8 | 1
030|  2.00 |   30.0 |  128 |  8 | 1
031|  2.00 |   60.0 |  128 |  8 | 1
032|  0.10 |    0.0 |  256 |  8 | 1
033|  1.00 |    0.0 |  256 |  8 | 1
034|  2.00 |    0.0 |  256 |  8 | 1
035|  5.00 |    0.0 |  256 |  8 | 1
036|  0.00 |   30.0 |  256 |  8 | 1
037|  0.00 |   60.0 |  256 |  8 | 1
038|  0.00 |  100.0 |  256 |  8 | 1
039|  0.01 |   30.0 |  256 |  6 | 1
040|  0.01 |   60.0 |  256 |  8 | 1
041|  0.01 |  100.0 |  256 |  8 | 1
042|  0.10 |   30.0 |  256 |  8 | 1
043|  0.10 |   60.0 |  256 |  8 | 1
044|  0.10 |  100.0 |  256 |  8 | 1
045|  0.50 |   30.0 |  256 |  8 | 1
046|  0.50 |   60.0 |  256 |  8 | 1
047|  0.50 |  100.0 |  256 |  8 | 1
048|  2.00 |   30.0 |  256 |  8 | 1
049|  2.00 |   60.0 |  256 |  8 | 1
050|  2.00 |  100.0 |  256 |  8 | 1
051|  5.00 |   30.0 |  256 |  8 | 1
052|  5.00 |   60.0 |  256 |  8 | 1
053|  5.00 |  100.0 |  256 |  8 | 1
... continued for sampling rates up to 4800 Hz

Available notch filters
===================================
num| hpfr  | lpfreq |  sfr | or | type
===================================
000| 48.00 |   52.0 |  128 |  4 | 1
001| 58.00 |   62.0 |  128 |  4 | 1
002| 48.00 |   52.0 |  256 |  4 | 1
003| 58.00 |   62.0 |  256 |  4 | 1
```

```
004| 48.00 |   52.0 |  512 |  4 | 1
005| 58.00 |   62.0 |  512 |  4 | 1
006| 48.00 |   52.0 |  600 |  4 | 1
007| 58.00 |   62.0 |  600 |  4 | 1
008| 48.00 |   52.0 | 1200 |  4 | 1
009| 58.00 |   62.0 | 1200 |  4 | 1
010| 48.00 |   52.0 | 2400 |  4 | 1
011| 58.00 |   62.0 | 2400 |  4 | 1
```

Appendix B
The neurogetparams Command Line Tool

```
BCI2000 Parameter Tool for Neuroscan Acquire V4.3
////////////////////////////////////////////////////////////////////
(C)2004 Gerwin Schalk and Juergen Mellinger
        Wadsworth Center, New York State Dept of Health, Albany, NY
        Eberhard-Karls University of Tuebingen, Germany
////////////////////////////////////////////////////////////////////
Signal Channels: 32
Event Channels:  1
Block Size:      40
Sampling Rate:   1000
Bits/Sample:     16
Resolution:      0.168 muV/LSB
Parameter file test.prm successfully written
```


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